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# TUNGSTEN DEPOSITS OF SOUTHERN KIANGSI, CHINA.[1]

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ABSTRACT.

The Kiangsi deposits normally supply about seventy per cent of the total output of the Chinese tungsten concentrates. They occur in an area of intensely folded Paleozoic and early Mesozoic sediments which are invaded by granite of late Jurassic age. Most of the deposits are hypothermal veins and some have pegmatite affiliations. The veins occur in granite and in sedimentary rocks not far from the granite intrusives. Larger deposits occur mostly near the top cupolas of granite batholiths. Greisenization without the development of topaz and tourmaline is the usual type of wallrock alteration in granite, while tourmalinization is a common type of alteration in argillaceous sediments near the veins. Greisenization generally decreases in intensity toward the deeper portions of the granite. Veins are composed mainly of massive quartz with some mica and various accessory minerals. Wolframite is the principal ore mineral, while cassiterite, bismuth minerals, molybdenite, and chalcopyrite are locally of economic importance. The veins are formed mainly by filling regular, parallel fissures; wolframite occurs almost exclusively in the parts of veins that fill fissures whereas cassiterite, if present, may replace the wallrock to a considerable extent. The ore-bearing fissures have a remarkably persistent strike and dip throughout the region and are tension joints which were produced by compressive or shearing stresses of a regional nature.

## INTRODUCTION.

FROM 1918 to 1937 inclusive, China yielded about 56 per cent of the world's tungsten production. About ninety-five per cent of

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the Chinese output comes from three southern provinces, Kiangsi, Hunan, and Kwangtung. Of these Kiangsi is by far the most important producer and normally yields about 70 per cent of China's production. All of these deposits are in an area of 14,000 square miles in the southern half of Kiangsi.

This report is based on three years of field work during 1934–1938. For detailed information on the Kiangsi deposits and the regional geology, the reader may refer to the writer's official report published by the National Geological Survey of China.[3]

The writer is indebted to Professor W. H. Emmons for his critical reading of this report and to Professors F. F. Grout and G. M. Schwartz for their direction in the laboratory work and critical reading of the report. He is particularly indebted to Dr. W. H. Wong, Minister of Economic Affairs, formerly Director of the Geological Survey of China, for his general supervision; to Mr. Ping Kao for his help in part of the field work; to Messrs. I. Ting, Hwei-ming Yen, and Sin-tien Chang for their assistance in the field work; and to Messrs. S. Chu, T. Y. Hsu, and S. F. Sheng for identification of the fossils collected.

## GEOGRAPHICAL FEATURES.

Nearly all of the tungsten and tin deposits of China occur in what is commonly called the Nanling ("Southern Mountains"). It is a broad region extending for about 1,500 miles across southern China. This vast area, including southeastern Yunnan, northern Kwangsi, northern Kwangtung, southern Hunan, southern Kiangsi, and the western parts of Fukien and Chekiang provinces (Fig. 1, inset map), trends generally ENE and NE to form the watershed between the Yangtze valley and the rivers that flow southeastward to the sea. Geologically, the region is characterized by zones of intensely and complexly folded moun-

[3] Hsu, K. C. and Ting, I.: Geology and tungsten deposits of southern Kiangsi. China Geol. Surv. Mem. Ser. A., No. 17, 1943. This report contains forty topographical and geological maps of tungsten districts, one regional geological and topographical map, and other illustrations. The text of the report is in Chinese with English summary.

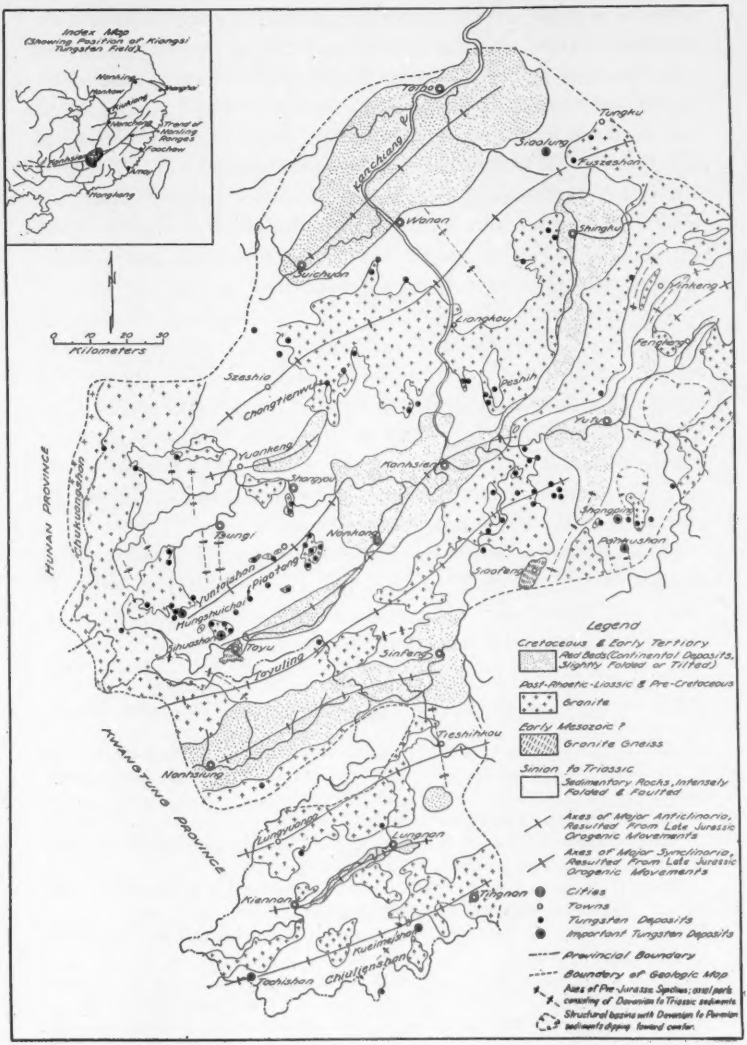


FIG. 1. Simplified geologic map of southern Kiangsi, China, showing the general geology and distribution of tungsten deposits.

tains, by widespread late Mesozoic granite intrusives, and by rich high-temperature metallic deposits, containing tungsten, tin, and some bismuth and molybdenum.[4] Tungsten deposits are richest in Kiangsi; smaller deposits occur in Hunan [5] and Kwangtung,[6] and some unimportant deposits are found in Kwangsi, Yunnan, and Fukien.[7] Tinstone is subordinate to tungsten ore in Kiangsi, but is the predominant ore in the provinces west of Kiangsi,[8] where the Kochiu mine in Yunnan is the chief producer. East of Kiangsi, in Fukien and Chekiang, neither tin nor tungsten are economically important, though molybdenite deposits are mined.[9]

Topographically, the Nanling region in southern Kiangsi is composed of a series of parallel and closely-spaced mountain ranges, which trend generally ENE or NE. These ranges are zones of the so-called complex mountains, though structurally they are parallel anticlinoria. They are maturely dissected, showing great relief and rugged topography. High peaks rise in places to 2,000 meters above sea level. The maximum difference in elevation in this region is 1,800 meters.

Between these mountainous belts lie several topographical troughs or intermontane basins, developed chiefly in the comparatively soft "Red Beds" of Cretaceous and Tertiary age. Most of the cities are located on the troughs or basins.

[4] Wong, W. H.: Les Provinces Metallogeniques de China. China Geol. Surv. Bull. 2, 1920; The mineral resources of China. China Geol. Surv. Mem., Ser. B, No. 1, 1910.

[5] Tien, C. C., Wang, H. C., and Hsu, H. T.: Reports on tin and tungsten deposits of Tze-hsing, Cheng-hsien, Kweitung, Lin-wu districts of Hunan province. Hunan Geol. Surv.

[6] Annual Reports of Kwangtung Geological Survey.

[7] Personal communications from various members of Geological Survey of China and provincial geological surveys.

[8] Meng, H. M. and Cheng, K.: Geology of the Hsianghualing tin deposits, Linwu, Hunan. Mem. Nat. Res. Inst. of Geol., Academia Sinica, 1935; Meng, H. M., Cheng, K., and Ho, T.: Geology of the Kochiu tin-field, Yunnan. Bull. Geol. Soc. of China, Vol. 16, 1937.

[9] Hsieh, C. Y. and Cheng, Y. C.: Geology and mineral resources of An-hsieh, Yun-chuan, and Yun-tai districts, Fukien. China Geol. Surv. Bull. 27, 1936; Meng, H. M. and Cheng, K.: Molybdenite deposits of Shihping-chaun, Tsing-tine district, Chekiang. Nat. Res. Inst. of Geol., Academia Sinica, Mem. 4, 1933.

The main stream here, the Kanchiang river, flows northward and finally discharges into Poyang lake and then into the Yangtze river. Kanchiang and its larger tributaries in southern Kiangsi are navigable by junks, thus greatly facilitating transportation to the interior parts of the Nanling region.

There are highways, good for automobiles, connecting all of the cities which are shown on the map (Fig. 1), and several main highways leading from Kanhsien to northern Kiangsi and Kwangtung.

## GEOLOGY.

*Stratigraphy.* The geological formations recognized in this region are tabulated below:

| Age | Formations | Max. thickness (in meters) |
|---|---|---|
| Lower Pleistocene | Red Clay | 15 |
| Late Tertiary | Kanhsien Gravel | 7 |
| | Unconformity (Nanlingian) | |
| Early Tertiary | Yutu Red Beds | 500 |
| | Unconformity (Yenshanian) | |
| Cretaceous | Loyao Red Beds | 600 |
| Late Jurassic | Unconformity (Yenshanian), granite, and tungsten deposits | |
| Lower Jurassic | Anyuan Coal Series | 400 |
| | Unconformity (Anyuanian) | |
| Lower Triassic | Tieshihkow Series | 300 |
| | Disconformity (Hercynian) | |
| Upper Permian | Loping Coal Series | 100 |
| | Disconformity (Hercynian) | |
| Middle Permian | Yangsin Limestone | 220 |
| Lower Permian | Chuanshan Limestone | 170 |
| Middle Carboniferous | Huanglung Limestone | 180 |
| Lower Carboniferous | Tseshui Coal Series | 150 |
| Lower Carboniferous | Changtung Shale | 250 |
| Devonian | Shiashan Sandstone | 700 |
| | Unconformity | |
| Pre-Devonian (Sinian-Cambrian to Silurian) | Metamorphosed argillaceous and arenaceous sediments | 3,000 |

The pre-Devonian metamorphic rocks form the backbone of the Nanling mountains and cover about one-third of the area mapped (Fig. 1). They consist of phyllites, slates, argillites,

quartzites, graywackes, and some mica schists and mica-quartz schists. The upper part of the metamorphic group is equivalent to the Tanchiapa shale (Silurian) in Hunan province.

The Devonian lies above the metamorphic series with a marked unconformity. It consists mainly of thick-bedded sandstones which are hard and resistant to weathering and erosion, stand out prominently wherever they are exposed, and serve as good key beds for working out the structure of the upper Paleozoic strata in the region. An impure limestone horizon in the middle part is fossiliferous.

The lower Carboniferous beds consist of shale, sandstone, and impure limestone, and the upper part carries a bed of anthracite coal. The middle Carboniferous is chiefly limestone.

The lower Permian is represented by a bluish gray fossiliferous limestone.

The middle Permian beds are fossiliferous limestone and shale, above which, separated by a disconformity, is the upper Permian (Loping) coal-bearing series with a bed of anthracite coal (fossiliferous).

The lower Triassic consists of shale and some limestone. It rests on lower beds disconformably.

The lower Jurassic formation (Anyuan Coal Series, fossiliferous) occurs about 40 miles to the north of Taiho city where it consists of conglomerate, sandstone, shale, and seams of bituminous coal. The formation lies unconformably upon older rocks ranging from Carboniferous to Triassic.[10] In the Yaokanshien tungsten district of southeastern Hunan, about 100 miles west of Tayu city, arsenopyrite-wolframite-quartz veins are introduced in the lower Jurassic coal series.[11]

The Cretaceous "Red Beds" formation consists of red sandstone, conglomerate, shale, tuffaceous beds, and in places rhyolite flows. Its age is such by fossils.[12] It unconformably overlies all

[10] Kao, P. and Hsu, K. C.: Geology of western Kiangsi. China Geol. Surv. Mem. Ser. A, No. 16, 1940.

[11] Personal communication from Dr. T. K. Huang, who found plant fossils of the said age in the country rocks of veins.

[12] Hsu, K. C. and Ting, I.: Notes on the origin and classification of Kiangsi tungsten deposits. China Geol. Soc. Ti-chi-lung-ping, Vol. 3, No. 3, 1938.

older strata and is in turn overlain by the Tertiary "Red Beds" formation which consists maily of red conglomerate, conglomeratic sandstone, and sandy shale with gentle dips.

The great masses of granite which intrude the area do not intrude Cretaceous beds. At the contact of the Cretaceous with granite, there are arkose sandstone and conglomerate with pebbles of granite, vein quartz, and greisen. Since the tungsten deposits are genetically related to the granite, these geologic relations fix the age of the tungsten deposits as pre-Cretaceous and post-Lower Jurassic.

*Orogenic History and Geologic Structure.* The orogenic history of China is now well understood through contributions of W. H. Wong,[13] V. K. Ting,[14] J. S. Lee,[15] C. C. Tien,[16] C. Y. Hsieh,[17] T. K. Huang,[18] and many other geologists. In many sections of southern China, five periods of orogenic movements are recognized. They are: Caledonian (late Silurian to early Devonian), Hercynian (Carboniferous and Permian), Anyuanian (late Triassic), Yenshanian (Phase A, late Jurassic, and B, between Cretaceous and Eocene), and Nanlingian (middle Tertiary). Each is represented by one or more widespread unconformities or disconformities.

In Kiangsi the main folding took place in (1) late Silurian, (2) late Triassic, and (3) late Jurassic. The Caledonian and Anyuanian folds trend generally NNW or N, but the late-Jurassic folds trend generally ENE or NE. The early folds are steep but mostly

[13] Wong, W. H.: Crustal movements and igneous activities in eastern China since Mesozoic time. China Geol. Soc. Bull., Vol. 6, No. 1, 1927.

[14] Ting, V. K.: The crustal movements in China. China Geol. Soc. Bull., Vol. 8, No. 2, 1929.

[15] Lee, J. S.: Geology of China. Thomas Murby & Co., London, 1939; Lee, J. S. and Chu, S.: Geology of southeastern Kiangsu. Nat. Res. Inst. of Geol., Academia Sinica, Mem.

[16] Tien, C. C.: Orogenic movements in Hunan. China Geol. Soc. Bull., Vol. 15, 1936.

[17] Hsieh, C. Y.: On the late Mesozoic-early Tertiary orogenesis and vulcanism and their relation to the formation of metallic deposits in China. China Geol. Soc. Bull., Vol. 15, 1936.

[18] Huang, T. K. and Hsu, K. C.: Mesozoic orogenic movements in the Pingsiang coalfield, Kiangsi. China Geol. Soc. Bull., Vol. 16, 1937.

minor folds, while the later folds are the major structures, forming anticlinoria and synclinoria that are approximately followed by the parallel mountainous belts and the "Red Beds" basins respectively (Fig. 1).

*Nanling Granite.* Late Jurassic folding was attended by the intrusion of great masses of Nanling granite, the emplacement of which was accompanied by formation of pegmatites, some of them tungsten-bearing, and by formation of the main tungsten veins in most of the granite masses. This rock covers about 20 per cent of the area mapped (Fig. 1). It forms great batholiths with stocks and cupolas. Larger masses of granite are exposed mainly along the axes of the major anticlines which trend generally ENE or NE. But the Chukuangshan batholith, about 160 miles long and 30 miles wide, on the border between Kiangsi and Hunan, has an elongation of north-south.

The granite intrudes the formations ranging up to Triassic, but its exposures are mainly surrounded by pre-Devonian strata. From the previously mentioned evidence, its age is assigned to late Jurassic. The Nanling granite is not metamorphosed and not gneissic. Two small exposures of granite gneiss, as shown on the map, may represent an earlier granite intrusion, possibly also Mesozoic, but no conclusive evidence can be given for this assumption.

Apophyses of pegmatite and aplite are common around the margins of the Nanling granite. Quartz veins are numerous around the margins but are rare toward the interior of the batholiths.

The mineralogical composition of the granite does not vary greatly throughout the area. It is commonly a biotite granite. Local varieties are muscovite granite, leuco-granite or alaskite, and hornblende-biotite granite. The average granite contains in volume proportion about 30 per cent quartz, 38 per cent orthoclase and microcline, 25 per cent silicic plagioclase (ranging from albite to oligoclase-andesine, $Ab_{70}An_{30}$), 7 per cent biotite with accessory muscovite, apatite, magnetite, zircon, and titanite. Tourmaline, fluorite, and lithium micas are rare in the fresh

granite, but may occur in quantity in the "pneumatolytically" altered rocks in the top or marginal portions of intrusives.

Other intrusives probably also Mesozoic include dikes and small bodies of diorite, monzonite, granite porphyry, quartz porphyry, lamprophyre, aplite, and pegmatite.

## TUNGSTEN DEPOSITS.

*Mode of Occurrence.* Many tungsten deposits occur within an area of about 14,000 square miles in southern Kiangsi. About eighty districts containing such deposits were being worked, at least intermittently, during the time of the survey. Most of the deposits occur either in granite or in sedimentary rocks near the granite contact. Three of these deposits are in sedimentary rocks near small exposures of granite porphyry, hornblende-quartz monzonite, or diorite, and several others lie in sedimentary rocks apparently four or five miles from the known granite exposures. Veins of the last two groups are mineralogically identical with the veins associated with granite, and lie in belts marked by scattered granite cupolas. It is thus reasonable to suppose that there may be granite bodies underlying these deposits. It appears probable, therefore, that all the tungsten deposits in this area are genetically related to the granite.

In general the tungsten veins occur not far from the contacts of granite intrusives, and an ideal dome-shaped contact of granite may serve as a surface of reference, which divides the tungsten veins vertically into two groups of nearly equal value. Sedimentary rocks and granite are commonly found in the same mining district in Kiangsi. At such places, tungsten veins may occur in the granite and in adjacent sediments, or they may lie mainly in granite or mainly in sediments, but it is rare to find many veins which extend from the granite to the sediments.

Since the degree of erosion and shape of intrusives are different from place to place, the tungsten deposits can be classified according to their occurrence in different parts of granite intrusives as follows:

1. Deposits above, in, or near granite cupolas or small stocks (veins in granite or in sedimentary rocks).

2. Deposits in or below the roof-pendants of granite batholiths (veins in granite or in sedimentary rocks).

3. Deposits around the marginal parts of granite batholiths (veins in granite or in sedimentary rocks).

4. Deposits in the granite batholiths themselves, without sedimentary rocks nearby (veins in granite only).

The deposits of the first group are richest and most numerous. Many deposits are included in the second and third groups, but they are not as rich. Deposits of the fourth group are rare and as a rule carry only low-grade ores. In central areas of the great granite batholiths there are no tungsten deposits nor even any barren quartz veins. Only in a few places at high altitudes there are lean tungsten veins, probably near the original contacts of the intrusives. Rich tungsten deposits obviously are associated with small rather than large granite exposures, and the top portions of granite intrusions are generally most favorable.

Although numerically more mining localities produce ore from veins in granite than from veins in sedimentary rocks, veins in granite yielded around 44 per cent, and veins in sedimentary rocks, generally more productive, yielded around 52 per cent of the total output of tungsten concentrates from Kiangsi in 1937. Placer mining in recent years contributed only about three to four per cent of the total production. Grade of ore varies considerably with local conditions. For instance, in large batholithic granite exposures, richer ore usually lies in sedimentary rocks above the granite contact, whereas in granite cupolas, like those in the Yuntaishan zone, veins in granite and those in sediments are equally valuable.

Most of the deposits in sedimentary rocks occur in pre-Devonian strata; only a few lie in Devonian sandstone. No ore has been found in Carboniferous to Triassic formations, but some veins in the Yaokangsien district extend upward to Lower-Jurassic sandstone. Veins occur in a variety of rock types which include phyllite, slate, argillite, mica schist, sandstone, quartzite, and graywacke.

Relative to the geological structure, most of the tungsten deposits lie in the broad cores of the major anticlinal zones, within which they follow the irregular extensions of granite intrusives (Fig. 1).

*Orebodies.* Tungsten deposits in Kiangsi and the entire Nanling region are mostly regular fissure-filling veins which consist mainly of massive quartz with wolframite, light-colored mica, and various other minerals. They are well-defined tabular bodies with plane walls and uniform strike and dip. Contacts between vein and wallrock are sharp and straight. Most of the tungsten veins were formed by filling the steep, parallel, tension joints in granite and sedimentary rocks. Some tin-tungsten veins in granite have wallrocks that are altered and carry cassiterite.

Veins range from paper-thin to three meters in width; those from 0.1 to 0.6 meter are most common. They are so closely spaced in many places that several may occur in a parallel position within a distance of one to two meters and are mined by one drift. At some places they are grouped together in typical sheeted zones, so that even the narrow veins are workable.

The veins are rather long notwithstanding their narrowness and are commonly persistent laterally and vertically. Only a few small deposits are characterized by scattered, short, discontinuous veins which are from several meters to tens of meters long. The common larger veins or groups of veins in most places are hundreds of meters in length. A few broad veins are 1,000 meters long. Most of the veins were opened up by shallow pits all along their outcrops and are easily traced and measured.

The problem of vertical extent of workable ore in veins can only be solved indirectly. In Kiangsi, there are only shallow underground workings, such as short adits and shallow shafts. The deepest shafts do not exceed 90 meters in vertical depth and nearly all of them have been operated profitably. Direct measurement to ascertain the vertical range of ore is not possible. But, at certain places where long and steep-dipping veins or group of veins extend from the upper part of a mountain down toward a steep canyon, the vertical extent of ore can be determined by the

difference in elevation between the highest and the lowest workings that are operated with profit.

In general the vertical extent of ore veins in sedimentary rocks, above or near granite cupolas or not associated with any igneous exposures, is greater than that of veins in granite. The Tachishan deposit has a vertical range of ore in larger veins from 260 to 300 meters, without considering the probable further downward extension of ore, which is still of good grade in the lowest workings. Depths of the same order are indicated at the Siaolung, Pankushan and Kweimeishan. At several places, such as Pankushan, Chialing (10 miles west of Shangping), and Talungshan (5 miles southwest of Piaotang), the topmost portions of veins become poorer in wolframite and richer in bismuthinite, or more rarely native bismuth.

Veins occurring in granite cupolas commonly are especially rich immediately below the granite-sedimentary contact. For about 70 meters from the upper contact, the decrease in value of the ore may be slight, but beyond that the ore may become considerably poorer with increased depth. The low-grade ore in the veins may extend 150 or even more than 300 meters below the contact. In a few localities, molybdenite becomes comparatively more abundant in the lower parts of veins.

The grade of ore in the ordinary hypothermal veins varies greatly in different mines. By taking the average of all the data for each district, it may be said that the clean ore carries from 0.5 to 4 per cent $WO_3$.

The Kiangsi tungsten veins have suffered little deformation since they were formed. They are only locally dislocated by faults with displacement of 2 to 3 feet. The scarcity of post-mineral faults is economically significant, for it simplifies mining. No evidences of crushing or brecciation after mineralization were observed in the tungsten veins.

In a few localities, in addition to the regular fissure-filling veins, there are other structural types of orebodies. A great lens-shaped wolframite-quartz body was observed at Chiulungnau, five miles west of Hungshuichai. The quartz body is about 50 meters wide

in the middle. It was introduced along the granite-phyllite contact with a kind of siliceous greisen on the side of granite. The body is composed of massive quartz with swarms of small wolframite crystals which are 0.5 to 1.5 cm. long, arranged parallel to the length of the quartz body, and showing a flow structure. At Peshih, there is a similar large quartz body with small wolframite crystals and a honey-combed structure, filled with some muscovite and pyrite. The phyllite wall rock is silicified. These large

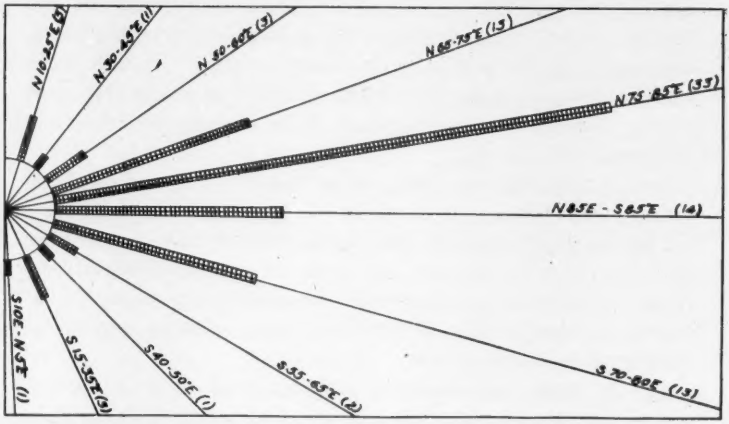


FIG. 2. Diagram showing the prevalent strikes of tungsten veins in southern Kiangsi. Longer rays represent common strikes, with direction indicated. Numbers in parentheses indicate number of localities.

quartz bodies do not contain high-temperature minerals, such as topaz, tourmaline, cassiterite, and molybdenite; possibly they were formed in a period later than the hypothermal stage.

*Origin of Ore-bearing Fissures.* In Kiangsi most of the tungsten veins strike nearly E–W. As shown in the diagram (Fig. 2), in 73 out of a total of 87 localities, the strikes of veins are within 25° of E–W. In each locality the veins are nearly parallel with the variation in strike of different veins commonly less than 20 degrees. In three of these localities, in addition to the E–W veins, there is another set of smaller, scattered, and discontinuous

veins which strike approximately N–S and intersect the major veins almost at right angles. At seven other localities the main productive veins strike NNW, N–S, or NNE, whereas the E–W veins are absent or poorly represented. The two sets of veins were, however, formed simultaneously, for they merge into each other at the crossings and are identical in mineral association, rock alteration, and other characteristics.

All of the tungsten veins have steep dips; in more than four-fifths of all the districts visited, the dips measure from 70° to vertical. And, in about four-fifths of these districts, the veins dip steeply to the north or are nearly vertical. Within each locality all the veins dip in the same direction at nearly the same angle. Hence on cross-sections of all the deposits the veins are nearly parallel.

Such a remarkable regularity in the strikes and dips of tungsten veins in an extensive area of about 160 by 90 miles indicates that the ore-bearing fissures in this region probably have a common origin and were formed by some regional stresses. Observations reveal that these fissures generally are tension joints which bear a definite relation to regional tectonics. Field evidence regarding their origin is stated below:

(1) At many localities where tungsten veins occur in granite, one or two sets of joints are noticed. One set of joints strikes approximately E–W and the other set intersects these approximately at right angles. Both joints are nearly vertical or dip steeply. The E–W joints are the major joints which may run continuously for considerable distance, forming steep bluffs or banks with straight and plane walls. Such joints are mostly filled by veins, whereas the other joints are indistinct, discontinuous, and in general are not filled by veins. The same sets of joints prevail in the granite over extensive areas even far from the mining districts.

(2) In many localities, such as Peshih, Shangping, and Piaotang, where tungsten veins occur in sediments, the veins are usually perpendicular to the bedding planes of country rocks. The country rocks, dominantly slates, phyllites, and sandstones, com-

monly strike N–S, dip steeply and are cut by steep-dipping E–W joints, which are partly or mostly filled by veins. Schistosity if developed is approximately parallel to the bedding planes and is therefore cut across by ore-bearing joints. The same attitude of metamorphosed sediments with the same cross joints prevail over some extensive areas between scattered tungsten deposits.

(3) There seems to be a close relationship between the trend of strong folds and the direction of joints, the latter generally normal to the former. A change in the trend of folds is accompanied by a change in joint directions. Thus, in the area between the cities of Tayu, Nankang, Tsungi, and Shangyou, where the late-Triassic folds as well as the Caledonian axes all trend NNW, nearly all the tungsten veins in the numerous localities strike ENE and dip steeply or vertically northward. But in the area southeast of Kanhsien and south of Yutu, where the late-Triassic folds trend mostly NNE together with local complicated structures, the tungsten veins in many localities strike WNW and some lie in NW, E–W, and N–S directions.

(4) At some localities local change in the attitude of sedimentary strata is not reflected by a corresponding change in the direction of veins. At Tachishan (Fig. 8) the country rocks, which consist of phyllites, slates, and some sandstones dip moderately WSW. Two sets of joints and veins occur. The major joints strike N75°W, dip 75°N, and are filled by a great many productive veins. The minor joints strike NNE and are filled by several small, discontinuous veins. At Pankushan mine, thick Devonian sandstone dips moderately southwestward and is cut by E–W and vertical tungsten veins. Thus, in both places, the joints as well as veins dissect the bedding planes obliquely.

(5) Veins occurring in different parts of granite intrusives and also in the nearby sedimentary rocks have practically the same strike and dip. For instance, there are four mining districts around the Sihuashan granite stock which is about 3 to 4 miles in diameter. Each district contains numerous parallel veins. All the veins strike between N75°E and N85°W and dip 70° to 90° toward the north. Some 20 miles west of Nankang city, there are

many tungsten deposits both in granite and in sedimentary rocks near the granite contact. Practically all the veins in this area strike between N75°E and N85°W and dip steeply northward. The same parallelism and regularity are observed in many other parts of the surveyed region. If the formation of ore-bearing fissures should have any relation to any primary structures of intrusive rocks, or to the surface of cooling of the solidifying granitic magma, we should expect the diversity of the strike of veins as they occur in different parts of intrusives. Evidently, this is not the case.

(6) At Hungschuichai, the tin-tungsten veins occur in a long, narrow shear zone in granite, which trends N40°W. This zone is 650 meters long and 20 to 80 meters wide. Within this shear zone, the granite is changed to greisen with ore veins in it. The greisen in places shows a distinct gneissic structure and consists of alternate bands of elongated, lens-shaped quartz grains and muscovite scales. This foliation strikes N10°–20°E and dips 70°–80° ESE, and thus makes an angle of about 50° with the trend of the shear zone. The coarse-grained biotite granite surrounding the mineralized shear zone does not show any noticeable parallelism of minerals. The greisen has a cleavage parallel to its foliation and a set of well-developed gash joints transverse to the foliation. The gash joints rather than the cleavage were followed by ore veins, which strike N70°–80°W and dip 60°–90° northward. All the ore veins throughout this mineralized zone have the same WNW strike even where the greisen does not show any distinct foliated structure. Thus, the ore veins are arranged *en echelon* and transect the narrow, northwest trending mineralized shear zone at an angle of thirty to forty degrees. Within the greisen zone, veins are numerous and closely spaced. They are from several centimeters to three meters wide, and are generally lenticular, widening in the central parts and thinning out toward the borders of the greisen zone. From these observations, we may conclude that the northwest-trending greisen zone is a shear zone, that the northeastern block was pushed northwestward relatively against the opposite block in a principally horizontal direction, that

the ore veins which are arranged *en echelon* in this zone are tension joints produced by shearing, and that the shearing stresses were probably active both before and after the period of greisenization.

Foliated greisen and transverse gash joints which are followed by wolframite-quartz veins were observed also at Changtienwu (some 20 miles north of Shangyou city) and Yangshan (some 7 miles west of Shingku city).

In short, the east-west and vertical ore-bearing joints are widespread and of regional nature. They are generally normal to the axes of the earlier steep folds and cut the north-south-striking and vertically dipping strata at right angles. Minor changes in the attitude of sedimentary strata are seldom reflected by a corresponding change in the strike of the associated joints, but a more pronounced change in the trend of folds is accompanied by a variation in direction of joints. Ore-bearing joints with the same strike and dip are developed in granite and in sediments without any regard to the shape of intrusives.

As already stated, the pre-Jurassic strata in this region were first closely folded with an approximately north-south trend, and later were subjected to a transverse, broad folding. Under such conditions the development of tension joints transverse to the trend of earlier folds in the anticlinal zones of the later broad folds seems to be a natural consequence. Since the granite is affected by the same joints, it is concluded that the granite was subjected to the same regional stresses and was torn apart by the same tension joints. The uniformity of joints in granite precludes the possibility of their relationship to any primary igneous structures, for fractures of the latter kind are apt to be diverse in strike and dip and to vary in direction with the contacts.

*Type of Deposits.* Production of tungsten in Kiangsi as well as the entire Nanling region is from veins which are more or less similar and are classified as hypothermal (some of them with pegmatite affiliations). At a few places, associated with the veins are some pegmatites, replacement deposits of cassiterite, and a mesothermal mineralization superimposed upon the hypothermal. Although these rare facies of deposits are economically unim-

portant, they are interesting because they show the successive changes in the course of differentiation of the "residual liquor" from the parent granitic magma.

*Pegmatites* in this area may be classified into the simple granite pegmatites and the ore-bearing pegmatites. The granite pegmatites are characterized by their simple mineral composition, consisting essentially of feldspars and quartz with or without a little muscovite. Green or brown micas, tourmaline, fluorite, topaz, and ore minerals are absent. The texture is coarser than that of the adjacent granite. The constituent minerals are tightly interlocked as in ordinary igneous rocks. The orthoclase is partly idiomorphic, and the quartz is coarsely granular. Drusy cavities do not occur. Such pegmatites occur as irregular masses in the marginal parts as well as in the central portions of batholiths. The wallrock granite is not greisenized or hydrothermally altered.

The ore-bearing pegmatites consist mainly of orthoclase and quartz with variable amounts of green or brown micas, fluorite, tourmaline, topaz, and commonly a little ore mineral such as molybdenite, cassiterite, or wolframite. They occur as dikes or pockets accompanying the main productive tungsten veins. The difference in shape between such irregular pegmatites and the regular veins, which sometimes occur nearby, is marked. At the southeastern part of Sihuashan, several pegmatites occur in an aplite dike which cuts through the granite. The pegmatites consist of orthoclase, granular quartz, books of green mica, molybdenite, and a little wolframite. The aplite wallrock is faintly altered with the development of some green mica and molybdenite. In the immediate vicinity of these dikes, some pegmatite and aplite dikes were cut through by wolframite-quartz veins (Fig. 3). At Chiulungshan (some 14 miles south of Shangyou city), several irregular pegmatites in alaskite consist dominantly of orthoclase and green mica with quartz and abundant cassiterite and wolframite. The alaskite wallrock is altered to a greisen. In one pegmatite at Pinpanloa (northwest of Nankang city), a drusy quartz crystal measured 75 cm. long and 35 cm. across. These ore-bearing pegmatites differ from the main productive hypothermal

veins by their dominant orthoclase, comparatively less abundant quartz, insignificant amount of ore minerals, less intense wallrock alteration, and irregular shape.

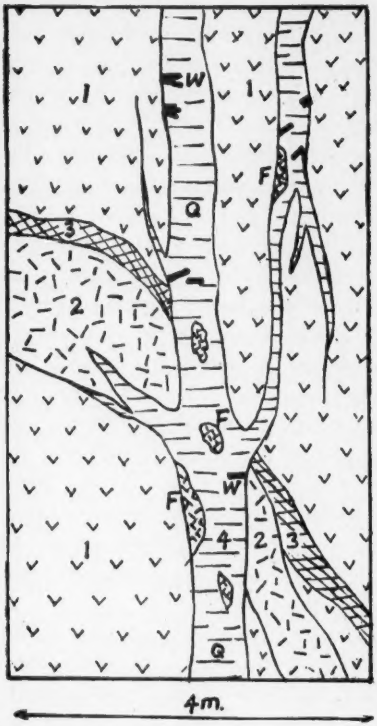


FIG. 3. Sketch (plan) of veins and dikes at the southern part of Sihuashan, showing sequence of mineralization. Granite (1) was intruded by aplite (2) and pegmatite (3) dikes, which were cut across by a hypothermal vein (4), composed of massive quartz (Q), orthoclase (F), wolframite (W), and other accessories.

The *replacement deposits of cassiterite* are those greisenized granitic rocks which contain notable amount of cassiterite. The greisenized granitic rocks near the tin-tungsten veins commonly

contain a little cassiterite, but ordinarily only in those greisens that are rich in white mica and fluorite, and deficient in quartz, does cassiterite occur in quantities sufficient to justify its recovery. In many tin-tungsten localities in the Yuntaishan zone, the mica-rich greisen is mined together with the veins and treated to recover the cassiterite. It is a greenish gray, medium-granular rock of sugary texture, and is composed mainly of muscovite or zinnwaldite (commonly 80 to 100 per cent white mica) with disseminated cassiterite, fluorite, and locally also a little molybdenite, bismuthinite, or scheelite; quartz is scarce or absent, and wolframite is rare. Such a mica-rock is called a greisen (mica-rich) because it resembles the normal greisen in texture and is always accompanied by the latter wherever it occurs. It occurs as lenses, pockets, or rudely tabular bodies associated with the tin-tungsten veins that are introduced in the upper parts of granite intrusives. These irregular bodies of mica-rich greisen are always bordered by the normal greisen which consists mainly of quartz and mica and which grades into the unaltered granite. Veins in the cassiterite-bearing greisen may be very thin, but the greisen itself may be one or two meters thick. At the southern border of Sihuashan, the greisen containing quartz stringers and cassiterite locally forms a layer, one meter thick, at the upper contact of granite with phyllite. Also it replaces several aplite dikes which intrude the phyllite roof rock.

It is noticeable that veins associated with the mica-rich greisen often carry as much wolframite as cassiterite, but in the greisen itself cassiterite is generally the only ore mineral present. Cassiterite is always accompanied by fluorite both in greisen and in veins, whereas in the non-stanniferous tungsten veins fluorite is rare.

By field evidence alone, the mica-rich greisen is undoubtedly a replacement of the granite, in which it occurs. The significant features of this rock are its dominant amount of mica, abundant fluorite and cassiterite, deficiency of quartz, and absence of wolframite.

The *hypothermal veins* are the only tungsten-producing deposits in Kiangsi. They are well defined tabular bodies, regular in strike and dip, forming groups of parallel veins in most places. Gangue minerals of the veins include quartz, muscovite, lithium-micas, orthoclase, fluorite, tourmaline, topaz, beryl, albite, sericite, chlorites, and calcite. Primary ore minerals include wolframite, cassiterite, scheelite, bismuthinite, molybdenite, pyrite, chalcopyrite, arsenopyrite, pyrrhotite, sphalerite, galena, native bismuth, magnetite, specularite, tennantite, and stannite. Along outcrops of veins or in the upper portions of them, there are various secondary minerals including limonite, hematite, kaolinite, pyrolusite, psilomelane, tungstite, bismutite, bismite, chalcocite, covellite, malachite, azurite, marcasite, scorodite, smithsonite, chalcedony, and wood tin.

Most of the vein is massive quartz in which other minerals are embedded. Orthoclase occurs in small amounts or is absent. Only in a few localities does it amount to more than one-fifth of the total volume of the veins. The texture of the veins is rather coarse. Tabular crystals of wolframite range from a few cm. to thirty cm. in length, being commonly 3–9 cm. long. Associated minerals are also coarse. Fine-grained texture is unknown. Minerals are unevenly distributed in the veins without any delicate crustification, but a roughly banded structure formed by successive crystallization of minerals has been noted. Mica, wolframite, cassiterite, and rarely tourmaline are commonly attached to the walls of the vein with a central filling of massive quartz. Wolframite and cassiterite also form isolated crystals embedded in massive quartz and irregularly distributed. Comb structure in quartz has been observed but is rather rare. Drusy cavities occur sparsely in nearly all the veins. Most of them are angular and several cm. across, bounded by several faces of imperfect crystals of quartz. Quartz, muscovite, bismuthinite, fluorite, cassiterite, scheelite, and topaz occur as beautiful crystals in such cavities.

Wolframite veins are more or less similar throughout the entire Nanling region, but there is some variation in mineral association

and in the proportion of minerals from place to place. The differences may be caused by any of the following factors:

(1) The distribution of tin ore in Kiangsi furnishes a good example of regional differences. Within the Yuntaishan zone, which is about 35 miles long east-west and about 15 miles wide, lying between Tayu, Nankang, Tsungi, and Shangyou cities, cassiterite occurs in considerable quantities in tungsten veins and in the associated greisens in many localities and is recovered as a by-product. Annual production of cassiterite concentrates, averaging 60 per cent tin, amounts to about 1,500 metric tons. In all the other tungsten localities outside of this zone, there is not enough tinstone to justify its recovery. Since other characters of the deposits are similar, a regional difference in the composition of ore solutions appears to be the only logical explanation for the distribution of tin ores. Regional differences may also explain the dominance of tungsten in Kiangsi and of tin in Kwangsi, Hunan, and Yunnan provinces.

(2) Type of wallrock is an important factor in determining the variety and relative amount of certain associated minerals in veins. Tungsten veins that have abundant mica in large plates always have argillaceous wallrocks, such as phyllite, slate, argillite, and mica-schist. Veins in granite contain much less mica (rarely more than one per cent), which is in distinctly smaller plates. In the veins in pure quartzite, mica is scarce. Tourmaline is invariably present in the altered argillaceous wall rocks but it is usually absent in granitic wallrocks. The variation in amount of mica and the presence or absence of tourmaline, however, bears no apparent relation to the grade of ore in veins.

(3) As already stated, bismuth minerals occupy higher horizons and molybdenite occupies lower horizons than wolframite in veins. Arsenopyrite is dominant in the upper horizons of wolframite veins in the Yaokangsien district of Hunan. In many localities in the Yuntaishan zone, cassiterite seems to be richer in the upper horizons of wolframite veins. In some places orthoclase-quartz veins may grade upward into pure quartz veins. These all seem explainable by zonal deposition of minerals.

(4) As stated below, a later, mesothermal mineralization was mainly responsible for the formation of sericite, chlorite, sphalerite, galena, chalcopyrite, tennantite, stannite, and part of the scheelite in tin-tungsten veins.

A *mesothermal mineralization* is clearly shown in many tin-tungsten mines. It brought a group of minerals that are characteristic of the intermediate vein zone into the higher temperature tin-tungsten deposits. Earlier minerals are replaced by later minerals or groups of later minerals. In Piaotang, a single topaz crystal is replaced by sericite, chlorite, sphalerite, chalcopyrite, and galena (Fig. 7). It is very common to find topaz replaced by sericite. Coarse masses of orthoclase are replaced by sericite and chlorite. Commonly orthoclase is replaced by sericite, which forms a light green, cryptocrystalline mass. Greisenized granitic wallrock is in places replaced by patches of late minerals which consist of chlorite, sericite, chalcopyrite, sphalerite, and pyrite. At Shialung mine, chalcopyrite forms large masses in tin-tungsten veins. It includes coarse quartz crystals, which were attacked and shaped into rounded residual masses. In many mines, pyrite and chalcopyrite in association with sericite and chlorite occur in distinct fractures and veinlets in the tungsten veins.

At Hungshuichai, a large quartz vein cuts across many tin-tungsten veins and the ore-bearing greisens. This vein consists of massive quartz with large vugs, and some pyrite, chalcopyrite, sphalerite, galena, sericite, and chlorite. Wolframite was not found in it. On both sides of this later quartz vein, sericite, chlorite, and the sulphides are abundant and replace the earlier vein-forming minerals and greisens. Evidently it represents a mesothermal mineralization that took place later than the pegmatitic and hypothermal tin-tungsten veins.

Thus, upon the earlier, high temperature mineralization, there was superimposed, in a number of localities, a definitely later mineralization. Minerals of the earlier period include quartz, muscovite, lithium micas, orthoclase, fluorite, tourmaline, topaz, beryl, albite, wolframite, cassiterite, bismuthinite, molybdenite, scheelite, native bismuth, arsenopyrite, pyrrhotite, and pyrite. Minerals of

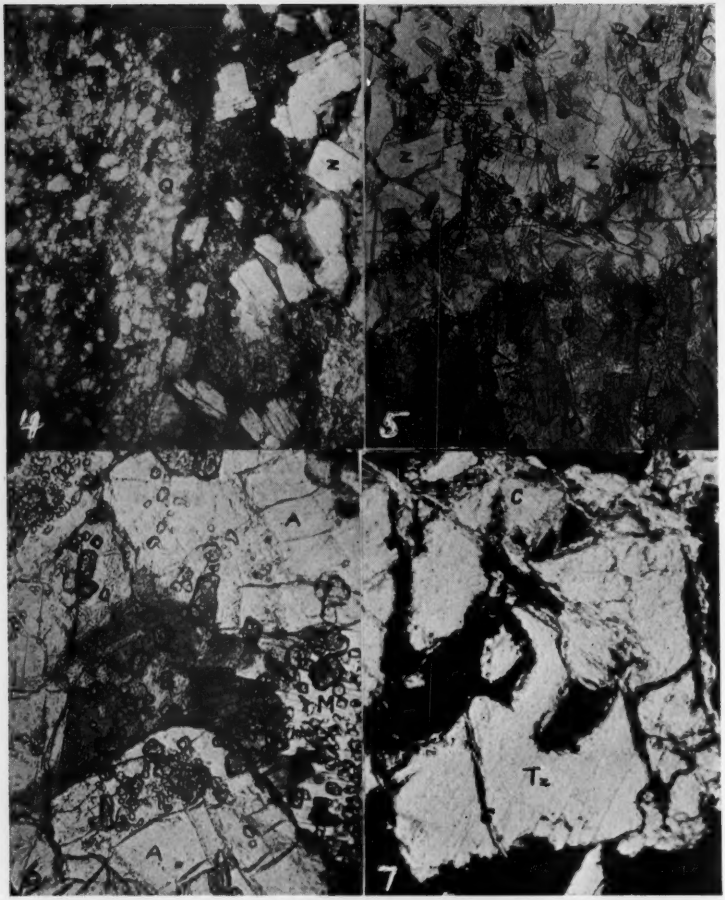


FIG. 4. Altered phyllite wallrock near tungsten veins at Talungshan. To the left is the fresher rock, composed of fragmental quartz (Q), biotite (B), and some sericite. To the right is the altered rock, composed of zinnwaldite (Z) metacrysts in biotite (B) aggregates. Thin section, one nicol. ×76.

FIG. 5. Intensely altered phyllite wallrock near tungsten veins. On the upper side rock is composed of zinnwaldite (Z) and tourmaline (T)

the later period include sericite, chlorite, chalcopyrite, pyrite, sphalerite, galena, tennantite, stannite, scheelite, quartz, and calcite. Some scheelite is deposited upon fine-grained chlorite in vugs and is therefore of late age. Stannite is closely associated with the late sulphides.

Occurrence of the later minerals in veins is local and sporadic. In many of the tungsten districts such later minerals are almost entirely absent.

Barren quartz veins occur in certain localities. Some of them are large and irregular bodies. Most of them do not contain any other mineral except massive quartz; a few have a little sericite. Alteration of wallrock is slight.

*Sequence of Mineralization.* From what has been stated the probable sequence of events following the cooling of the outer shell of granite magma can be outlined as follows:

(1) Cooling and solidification of the outer shell of granite batholiths.

(2) Fracturing of the solidified magma shell and the invaded rocks by some regional stresses which were compressive or shearing stresses, resulting in many tension joints.

(3) Formation of aplites, accompanied and followed by pegmatites with insignificant metallic minerals.

(4) Rise of the main metalliferous fluids laden with "mineralizers"; greisenization and formation of replacement deposits; deposition of tin-tungsten veins with some bismuth and molybdenum sulphides but little base-metal sulphides.

(5) Rise of hot aqueous solutions containing base-metal sulphides with only a little tungsten and tin; solutions ascending

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crystals. The lower side is next to the vein and is composed entirely of tourmaline. Thin section, one nicol. ×76.

FIG. 6. A rare type of greisen in Fuszeshan, composed of spinel (small octahedral crystals with high relief), biotite (dark area in center of picture), muscovite (M), and andalusite (A) in square crystals. Thin section, one nicol. ×108.

FIG. 7. Topaz crystal (Tz) from veins in Piaotang is replaced by sericite (S, gray fibrous mineral in veinlets), chlorite (C, gray area with radiated structure), and sphalerite, chalcopyrite, galena, and pyrite (all black in topaz and around it). Thin section, one nicol. ×90.

mainly along old channels, working through the fractures of veins. Deposition of barren quartz.

The successive changes in composition from aplites through pegmatities to ore veins are the constant increase in the proportion of silica, in the amount of "mineralizers," and in the concentration of metallic and rarer elements and a decrease in the amount of feldspar.

The tungsten veins are classified as hypothermal deposits (and some have pegmatite affiliations). They possess the characters of both pegmatites and hypothermal veins. The characters of tungsten veins are: (1) The mineral species of the deposits are not different from those of pegmatites. (2) Texture of the veins is rather coarse. (3) As indicated by the amount of certain minerals in the veins and the wallrocks, the concentration of volatile matter such as F, B, $H_2O$, Li, etc., was probably at the climax and the vapor pressure of the system was probably at the highest point during the formation of the veins as compared with the famous Niggli diagram of two-component system. (4) Quartz is the dominant gangue, whereas orthoclase occurs only in small amounts or is absent. (5) The regularity and persistence of the veins are comparable with those of ordinary mineral veins rather than pegmatites. (6) They cut across earlier pegmatites at places.

*Wallrock Alteration.* (1) *Greisenization.* Granite or aplite wallrocks of tungsten veins are altered to greisen from one-half to two meters from the contact with veins. The intensity of alteration generally increases toward the vein and decreases from it. On the basis of difference in intensity of alteration, several zones may be recognized.

The outer zone is an altered granite. Megascopically this rock still retains its main features of granite, except that the black biotite flakes are gone. Microscopically, most of the biotite and part of the feldspars of the granite are replaced by white mica (muscovite or zinnwaldite). In places some small grains of secondary quartz are associated with the white mica inside the feldspars. Where cassiterite occurs in the veins, the white mica

in the altered rock is always accompanied by fluorite. In general the soda-lime feldspar seems to be more altered than potash feldspar. Quartz remains intact. Leucoxene and some hematite are commonly associated with the muscovite where it has replaced the biotite. Zircon grains are retained in the muscovite. The resulting rock shows coarse grains of the original minerals of the granite, replaced by secondary minerals of much smaller sizes, which cluster inside their host. Thus there is clear evidence of metasomatic replacement in such rock which has not suffered a complete recrystallization.

The inner zone, next to the vein, is the normal greisen. It is megascopically a compact, medium textured, sugary grained rock of a light bluish gray or greenish gray color. Microscopically it consists of anhedral grains of quartz and white mica, with or without some fluorite. Biotite and feldspars of the original granite completely disappear. Zircon grains are included sparsely in the white mica and surrounded by pleochroic haloes. Cassiterite and sulphides like bismuthinite, molybdenite, and pyrite may be impregnated sparsely in the rock. Topaz occurs in some tin-tungsten veins but it is rare in the greisen.

Minerals in the normal greisen are even-granular and have a mosaic structure. Quartz usually makes up about fifty-five to seventy per cent of the rock, the rest being mainly white mica. No distinction can be made between the original quartz of the granite and the late quartz. A general recrystallization has destroyed the clear evidence of metasomatic replacement.

As already stated, there is a mica-rich greisen which occurs locally as patches between the ore vein and the normal greisen, or as rudely tabular bodies bordered by the normal greisen and altered granite and containing very thin quartz-orthoclase veinlets. The profound chemical change in the development of such rock is indicated by the fact that, in the mica-rich greisen, not only all the feldspars and biotite but most of the quartz of the original granite are gone. The porosity of this rock is rather high.

Contacts between these zones are gradational. But the gradational zones are generally narrow.

"Siliceous Greisen," containing up to about eighty-five per cent

quartz, occurs locally alongside some large, closely-spaced wolframite-quartz veins.

Greinsenization is most intense at the upper portions of granite cupolas, where the tenor of ore in veins is usually higher. From the contact surface downward, mica-rich greisen becomes less common, and the zone of normal greisen becomes thinner. Toward the deeper portions of the granite, normal greisen may be absent; here the granite wallrock is only slightly altered. At such places the tenor of tungsten ore is low, and cassiterite is rare even in those veins which carry tin-ore in their upper portions.

In one part of Fuszeshan there is a peculiar kind of greisen near tungsten veins. The wallrock of the veins which are located in granite-phyllite contact is altered to an aggregate of muscovite, andalusite, biotite, spinel, and tourmaline. Toward the vein contact the rock is composed wholly of muscovite and tourmaline. The mineral composition of the rock indicates that the original rock was probably phyllite which was first contact metamorphosed and then tourmalinized and muscovitized. At Tsingtung district, on the summit of the Chukwanshan mountains, the granite country rock throughout the mining area is speckled with black tourmaline, and the wallrock of the veins is heavily tourmalinized. Outside these two localities tourmaline is rare in the greisenized granite wallrocks.

Thus, in Kiangsi, the greisenization of the granite accompanying the formation of non-stanniferous tungsten veins is simply a process of muscovitization plus the liberation of silica from the silicates. That the common greisen consists only of quartz and white mica indicates a probable loss of lime, soda, and possibly of iron and magnesia through the leaching action of ore-bearing solutions and a residual concentration of silica, alumina, and potash. The common greisenization thus appears to be mainly a hydrothermal alteration of the granite.

The development of the mica-rich greisen indicates not only the leaching of certain bases but also the removal of a large quantity of silica from the original granite. The chemical reaction by which silica was removed is unknown, but there are two possible explanations: (1) Silica was removed by the ore-bearing solution

which had become highly alkaline; and (2) silica was removed by the action of hydrofluoric acid which was produced by the reaction of stannic fluoride with water.[19] The last assumption would explain the constant association of cassiterite and fluorite and the abundance of both minerals in the greisen, but such a reaction would require an acid solution which however is contrary to general belief.

(2) *Alteration of Other types of Wallrocks.* Where argillaceous rocks, such as phyllite, slate, argillite, and mica-schist are cut by tungsten veins, tourmaline and muscovite (in metacrysts) commonly occur in the wallrocks (Figs. 4 and 5). At many places, tourmaline does not occur in veins, but was observed in thin sections of the wallrocks. In most cases alteration of the phyllite wallrock, as indicated by change in color and texture, can be detected only within one meter from the veins.

Microscopically, the phyllites are fine-grained rocks with fragmental texture and bedded structure, composed mainly of sericite, biotite, and quartz. In these rocks, tourmaline and white mica occur first as scattered metacrysts among the fine-grained biotite, sericite, and quartz (Fig. 4). They replaced selectively the bands which are dominated by biotite and sericite. Nearer the vein contact, these metacrysts become more abundant until the whole mass of rock is composed of white mica and tourmaline (Fig. 5). At other places, the intensely altered wallrock may be composed entirely of white mica, or of tourmaline, or of tourmaline and quartz. The resulting rock generally has a sugary texture. Banded or zonal distribution of minerals in such rocks is common.

Partly altered wallrocks are more common than completely altered ones. Silicification of argillaceous wallrocks is uncommon.

Quartzite and quartzose sandstone are generally altered only slightly by the introduction of ore veins. However, tourmaline and white mica are common in the argillaceous bands. At Yehshang, white quartz-sandstone near the ore veins is spotted with short tourmaline crystals, which occur in the spaces between the

[19] Daubree's reaction, see Lindgren's Mineral Deposits, p. 651.

quartz grains, indicating that the cementing material of the rock was probably used up to form the new mineral.

A diorite dike is cut by several tungsten veins at Tachishan. The fresh rock is made up chiefly of green hornblende and andesine, with some quartz, biotite, apatite, and ilmenite. In the altered rock, the hornblende is replaced by aggregates of fine-grained biotite and epidote; the feldspar is replaced by white mica, quartz, and epidote. Apatite has recrystallized into long, slender crystals; some tourmaline and pyrrhotite also appear. At Piaotang hornblende monzonite which is altered near the ore veins carries actinolite, epidote, chlorite, calcite, pyrrhotite, sericite, and zoisite.

*Mineralogy.* Wolframite is the only tungsten mineral that occurs in important amounts in all the Kiangsi mines. It occurs almost exclusively in the parts of veins that fill fissures and is very rare in the greisenized wallrock. It is unevenly distributed in veins, especially in larger veins. It commonly forms tabular crystals parallel to the orthopinacoid without terminal faces. The tabular crystals are twinned on orthopinacoid and are commonly grouped in divergent positions with their c-axes converging toward the vein wall and diverging toward the middle of the vein. Columnar crystals, inter-penetrating blades, and irregular cleavable lumps of wolframite are also common. Analyses of 93 per cent pure wolframite concentrates indicate that the ratio of FeO to MnO varies in different localities, and that this ratio approaches 2 : 1 at the Kweimeishan district, 3 : 2 at Pankushan and Siaolung, 1 : 1 at Tachishan, and 2 : 5 at Shangping.

Scheelite occurs in small quantities in most of the veins, but constitutes about 5 per cent of certain concentrates. Some of it replaces wolframite along cracks. It was deposited in two periods, one late in hypothermal mineralization, and the other during mesothermal mineralization.

In part of the area cassiterite is present in tungsten veins and is recovered. It occurs both in the veins that fill fissures and in the greisenized granitic wallrock. The amount of cassiterite present is approximately proportional to fluorite, but that is not true of wolframite. Cassiterite occurs mostly as euhedral crystals (up to 6 cm. across), but in some rich deposits anhedral cassiterite

occurs intergrown with and replacing wolframite. In certain veins cassiterite is rich in the upper zones but less rich below in the wolframite zones. The vertical range of cassiterite in veins appears to be smaller than that of wolframite and the cassiterite is overlapped on both ends by wolframite. Such a zonal distribution of tin and tungsten ores is not known in many other regions; it is usually reported that wolframite occupies a higher horizon than cassiterite in the same veins. The explanation may be that the relative concentration of ions or compounds in the vein-forming fluid is an important factor in determining the sequence of deposition of the metals, for the solutions probably had a high concentration of tungsten and a very low concentration of tin.

Bismuthinite and molybdenite are present in many of the ores. In eight localities bismuth minerals (bismuthinite, native bismuth, bismuth carbonate and ocher) are recovered as a by-product. Bismuthinite forms long, columnar crystals in quartz or more commonly acicular crystals in drusy cavities.

Pyrite, arsenopyrite, pyrrhotite, chalcopyrite, and sphalerite are present in small amounts in tungsten veins. At Yaokanshien district arsenopyrite was once recovered as a by-product, and several veins at Shialung contain 4 per cent copper in the form of large masses of chalcopyrite. Minute inclusions of chalcopyrite in sphalerite (formed by exsolution?) are common. Galena is present in several localities.

A little stannite was found in a polished ore from Piaotang. It is closely associated with sphalerite, chalcopyrite, pyrite, galena, and tennantite and has mutual boundary with sphalerite and chalcopyrite, indicating contemporaneity.

Magnetite is not common in the veins, but in one locality some veins contain large magnetite masses. A little specularite is present in a few places.

The chief gangue mineral of the tungsten ores is quartz which generally constitutes 90 to 97 per cent of the total volume of the veins. It is mainly milky white and massive and under polarized light is seen to be composed of very coarse anhedrons. Drusy quartz crystals up to 10 cm. long are fairly common. Quartz has a long period of crystallization, and, therefore, we find that al-

though most of the hypothermal minerals are embedded in massive quartz, crystals of many minerals like fluorite, scheelite, muscovite, bismuthinite, and even topaz and cassiterite are sometimes deposited on drusy quartz.

Orthoclase is plentiful in granite pegmatites and in the tungsten-bearing pegmatites, but occurs sparingly or is absent in the ordinary hypothermal tungsten veins. It has a long period of crystallization; it may form veinlets in wolframite and a central filling in veins including many minerals. Albite is sparingly present, generally associated with orthoclase. Microcline, so far, has not been found in tungsten veins.

The micas, muscovite, zinnwaldite, and more rarely lepidolite, are widespread and occur in pegmatites, in all tungsten veins, and in their wallrocks. They constitute from less than one per cent to nearly 20 per cent of the volume of veins, ordinarily about one per cent or less. Golden-colored zinnwaldite often forms large plates lining the walls, but grayish muscovite commonly occupies druses. Biotite is not present in tungsten veins or pegmatites, but occurs in certain recrystallized wallrocks. A small amount of sericite is present in many ores. It is a late mineral, occurring in fractures and replacing earlier minerals such as orthoclase and topaz.

Tourmaline, generally black, occurs in most of the argillaceous wallrocks of veins, but is only sparingly present in certain veins. Topaz on the other hand occurs in some veins but is rare in the altered wallrocks. In Piaotang there are narrow veins with zinnwaldite lining the walls and a central filling of topaz. Replacement of topaz by sericite is common. Fluorite is widespread in tin-tungsten veins and wallrocks, but is rare in the non-stanniferous veins. It is colorless, greenish, or purple.

Beryl is sparingly present occurring as euhedral crystals or as masses in the vein quartz. A little garnet is noted in a scheelite-bearing pegmatite. Andalusite and ceylonite are present in the wallrock of veins at Fuszeshan.

The chlorites, daphnite, penninite, and thuringite occur abundantly in several tin-tungsten districts. Daphnite and penninite form dark green, coarse rosettes, up to 7 mm. in diameter, closely

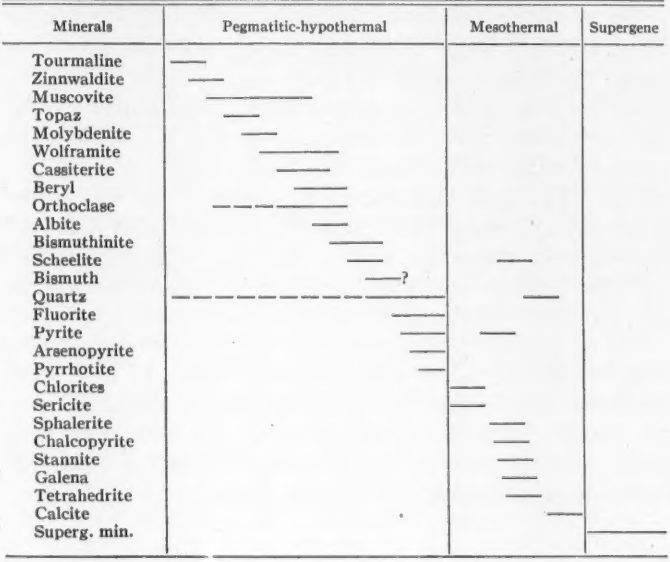
associated with chalcopyrite, sphalerite, galena, and pyrite. They are formed mainly by replacing feldspar in the veins. Thuringite occurs in fine granular aggregates. A little calcite is present in the vugs of some veins.

The usual oxidation products of the sulphides are present in many of the veins. Bismutite, the basic bismuth carbonate, is common, forming perfect pseudomorphs after bismuthinite. Molybdite is noted but is rare. Marcasite shows colloform structure and is probably secondary after pyrrhotite. Scorodite was found in Sihuashan, forming small leek-green crystals or granular aggregates traversing arsenopyrite.

Supergene alteration of scheelite and wolframite to tungstite is not rare. Wolframite crystals are rarely free from limonite. Secondary manganese oxides, psilomelane and pyrolusite, are common in veins, the primary source of which may be wolframite. Wood tin is noted on a polished section of wolframite ore.

The order of formation of various minerals is shown in the following table.

SEQUENCE OF MINERALS IN THE TUNGSTEN VEINS.



## MINING.

Tungsten deposits in southern China were first discovered at Yaokangsien of Tzusin district in southeastern Hunan in the first decade of this century. A prospector, searching for lead deposits, found wolframite in detritus below the vein outcrops. The material was later identified as wolframite by chemical analysis. Later, wolframite was found in placers at Sihuashan of Tayu district in southern Kiangsi. These two deposits were not developed actively until World War I, when the high price of tungsten and the ease of mining the rich placer deposits at Sihuashan attracted tens of thousands of laborers to the area. Prospecting by these laborers from 1916 to 1918 resulted in the discovery of numerous tungsten deposits in southern Kiangsi. Most of the first-worked deposits were placers. As the placers soon became exhausted, veins on the mountains and hills were located and mined. Since 1925, output from placer mining has been much less than from lode mining. In recent years concentrates from placer mining constitute only about three to four per cent of the total output of Kiangsi.

The mining methods in all the camps are still simple and crude. Hand drilling ("single jack") and black powder are universally used. Open cuts along the vein outcrops, short adits and shallow shafts are adopted, depending upon the local topography and the position of the veins. No electric power has been used. The crude ore is first hand sorted, then hand crushed and jigged or panned. The crude concentrates thus obtained are sold to the government agencies, which treat them by somewhat improved methods of hand crushing, jigging, sluicing, and drying, and finally pack them in hemp bags for export. Concentrates high in cassiterite are further treated by magnetic separators.

The inefficiency of hand labor, and the large number of men engaged make the cost of production rather high. In 1937, some 28,000 men were engaged in active mining in the camps of southern Kiangsi. This figure did not include the government employees and other laborers who were engaged solely in concentration, transportation, and other indirect work.

Mining is carried on in many places by small companies, and small groups of men. Several years ago the government started to operate several large mines with improved methods and this production is increasing in proportion to the output of native mines.

The first shipment of Chinese wolframites was made in 1914, but active mining started in 1917 when the annual production increased to more than one thousand tons from insignificant figures in the years before. From 1918 to 1937 inclusive, China produced 163,042 metric tons of concentrates out of the world's total of 292,357 tons in the same period.[20] The sharp drop in China's export of tungsten concentrates since 1940 was due entirely to transportation difficulties caused by the war which has never interfered with production, for the stabilized fighting fronts are far away from this productive area.

The tungsten concentrates of Kiangsi are of good grade. They are high in tungsten and low in impurities. The final mixed concentrates generally contain about 70 per cent $WO_3$, 11 per cent MnO, 12 per cent FeO, less than 1 per cent Sn, less than 0.1 per cent As, and less than 0.3 per cent S.[21]

In peaceful times, most of the Kiangsi concentrates were shipped to Kanhsien city by trucks and small junks, and some partly by porters. From Kanhsien to Kiukiang, a river port on the Yangtze, they were transported by boats towed by steam launches, from Kiukiang to Shanghai by steamships, and finally exported from Shanghai. During recent years they were shipped in various ways, and export centers shifted from place to place as a result of war difficulties.

The Kiangsi tungsten deposits, especially the more important deposits, are large and high grade. They possess tremendous ore reserves. In spite of crude mining and concentrating methods, they have been the world's leading producers for more than twenty years. An increased production from Kiangsi is to be expected after this war, when the larger mines there will no doubt be equipped with modern machinery for mining and milling.

[20] Data from the Minerals Yearbook, published by the U. S. Bureau of Mines.
[21] Generalized data from analyses of the Kiangsi concentrates in part of 1937.

## DESCRIPTIONS OF SOME IMPORTANT DISTRICTS.

In southern Kiangsi, the more than eighty tungsten districts or subdistricts are shown on the map (Fig. 1) as dots. Of these, seven more important ones are indicated (Fig. 1) by dots surrounded by small circles and their locality names. Two are located near the south margin of the map; two near the southeast margin; two in the west-central; and one in the northeastern corner. All these localities are briefly described.

*Tachishan.* The Tachishan district (Fig. 8) lies on the summit of the Chiulienshan mountain range. The highest peak in the mining district is 1,100 meters above sea level. The country rocks are phyllite, argillite, and quartzite of Siluro-Ordovician age. Several diorite dikes are found near the deposits, and granite is exposed three miles north of this district. The deposit, discovered in 1918, has been one of the leading producers.

Tungsten veins are formed by filling two sets of rock joints. The major joints and veins strike N65°–80°W and dip 70°N. The veins consist mainly of quartz, with wolframite, zinnwaldite, and other accessory minerals. The wallrock is heavily tourmalinized. Veins are localized in several sheeted zones. The most productive part is near Aotzuchieh, where some 24 parallel veins, with an aggregate width of 9.6 meters, occur in a zone 90 meters wide. The individual veins are from 0.15 to 1.5 meters wide. Some large veins have been traced continuously for 650 meters along the strike. At Shushanwe, twenty parallel veins, each 0.10 to 1.0 meter wide, with an aggregate width of 5.6 meters, occur in a zone 270 meters wide. All these veins are being mined profitably through short crosscuts and drifts. The elevation difference between the highest and lowest workings along the same group of veins is 300 meters, which may be taken as the proved minimum vertical extent of commercial ore. There is no reduction in the grade of ore in the deepest workings of this district. The clean ore from veins averages about 2.5 per cent $WO_3$. As indicated in the longitudinal projection (Fig. 9), all the native mines were being worked along the upper portions of veins, leaving the deeper parts untouched.

*Kweimeishan.* The Kweimeishan district is located also on the summit of the Chiulienshan range, at an elevation of about 1,000 meters above sea level. The country rocks are dark gray Cambro-Ordovician quartzite with some intercalated phyllites, striking

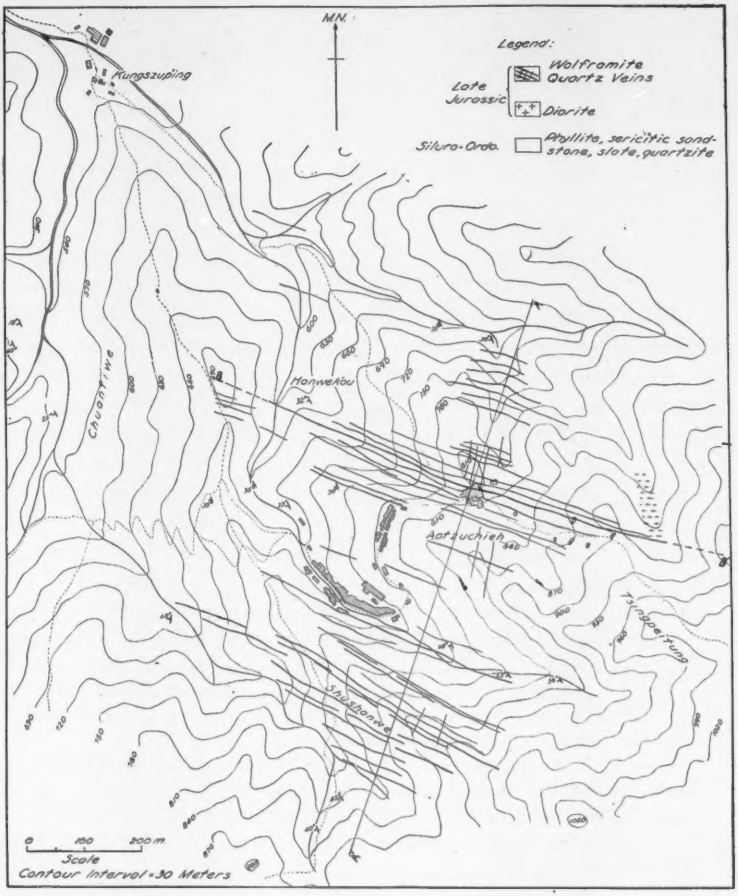



FIG. 8. Geologic map of Tachishan tungsten district, Kiennan, Kiangsi, China.

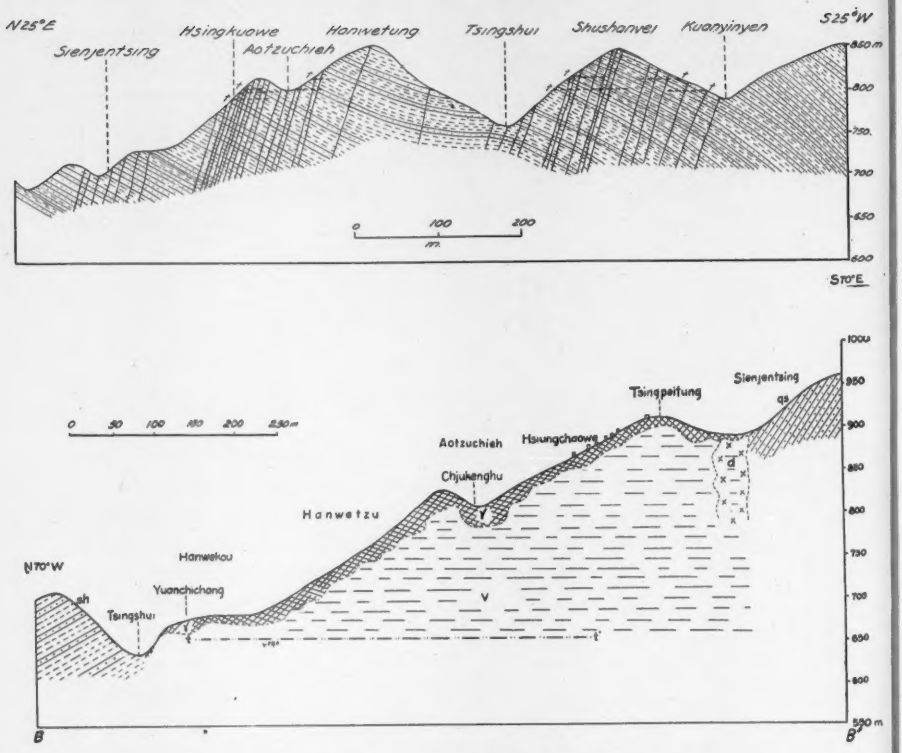



FIG. 9. (Upper) Section A—A′ of Tachishan tungsten district showing ore veins and country rock, which consists mainly of phyllite and quartzitic sandstone. (t), the crosscuts of some small mines.

(Lower) Longitudinal projection B—B′ along a group of veins of Tachishan district. Cross-hatched areas are parts of veins mined out by native mines; t—t′ a new adit operated by a government mine; dash lines show the partly proved downward extension of ore; (d) a diorite dike; and (Sh) phyllite.

NNW and dipping moderately southwestward. A granite cupola is exposed on the western foothill, about 300 meters lower than the vein outcrops. This deposit, discovered in 1918, has yielded considerable ore. In recent years, production has declined considerably due to the difficulties of deeper working by crude methods.

Closely-spaced tungsten veins occur on the ridge of the mountain. The veins strike N20° W and dip steeply eastward. They occur in a sheeted zone 1,500 meters long and from 200 to 500 meters wide. Veins are wider in the middle part of this zone. The most productive part is Ma-ao, where some thirty parallel veins with an aggregate width of 20 meters occur within a zone 200 meters wide. The veins are composed mainly of quartz with wolframite, and are characterized by the scarcity of other associated minerals. The wallrock is slightly tourmalinized. The clean ore averages about 2.9 per cent wolframite; some parts carry as much as ten per cent wolframite. The veins are worked from the top of the mountain by many shafts, some of which have reached a vertical depth of ninety meters, without any reduction in the grade of ore nor in the width of veins. The vertical extent of ore seems to be considerable.

The granite on the western foothill also contains some low-grade wolframite-quartz veins, which have the same strike and dip as those on the top of the mountain.

*Sihuashan.* The Sihuashan district is on a high mountain near Tayu city at an elevation of some 800 meters above sea level. It is on the south-central part of a granite stock which covers an area 3 to 4 miles in diameter. There are three other tungsten districts located around the same granite stock. Most of the tungsten veins in these districts occur in granite and end abruptly against the granite-phyllite contact.

The mining area at Sihuashan is about 2,000 meters long from north to south and 1,200 meters from east to west. Within this area ore veins are numerous, all striking between N70°E and E, and dipping 70°–90° northward. North-south traverses through the district disclosed some 200 parallel veins more than 10 cm.

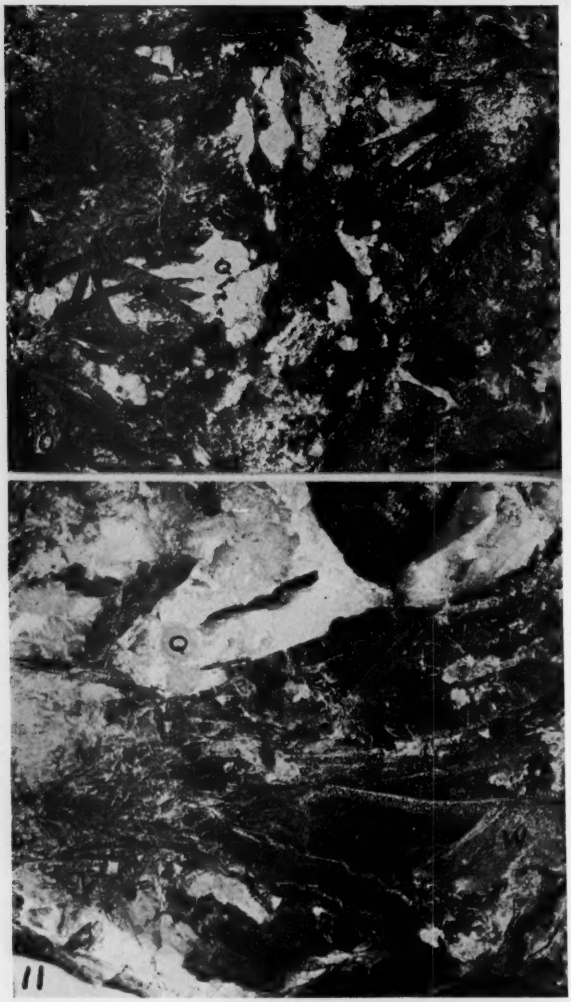



FIG. 10. Wolframite crystals (black) in massive quartz (Q, white) from a four-inch vein near Siaolung. Right and left edges of the picture are near the original sides of the vein. Natural size.

FIG. 11. Wolframite crystals (W, black) in massive quartz (Q, white) from a vein in Tachishan. Reduced one-third.

wide. They range up to two meters wide, but most are between 15 to 40 cm. They have an aggregate width of 51 meters. Some wide veins have been traced more than 800 meters along the strike, but narrow veins are much shorter and are discontinuous. All of them carry wolframite and most of them have been mined along their outcrops by numerous small open pits (Figs. 15 and 16).

The veins consist mainly of quartz, with some orthoclase, muscovite, cassiterite, molybdenite, and other accessory minerals. The richest ore is near the granite-phyllite contact. Toward deeper parts of the granite the grade of ore becomes much lower. Probably no great depth of commercial ore can be expected in this district, although it has been one of the largest producers in Kiangsi.

*Hungshuichai.* The Hungshuichai district, discovered in 1918, is reached from Tayu only by trails, but has been one of the leading producers of tin and tungsten concentrates. It is located on a "finger-tip" of a granite batholith. There are several other tungsten districts nearby which are located on separate "fingers." The mineralized zone at Hungshuichai is a narrow shear zone in coarse-grained granite which intrudes in pre-Devonian phyllites, schists, and quartzites. This zone is 650 meters long and 20 to 80 meters wide, trending N40°W. The granite within the mineralized zone has been changed entirely into greisen, in which are short, lenticular ore veins striking N70°–80°W and arranged *en echelon* in this narrow zone. The aggregate width of the ore veins varies from 5 to 12 meters. Wolframite is produced from the veins, while cassiterite is produced from both the veins and the mica-rich greisen. The veins consist mainly of quartz, orthoclase, mica, cassiterite, wolframite, fluorite, chlorite, and other accessories.

The mineralized zone is mined by a number of open pits (Fig. 14), some of which reached a depth of thirty meters. Production of cassiterite is a little more than twice as much as wolframite. The ore is of high grade, but exact data are not available.

*Shangping.* This district was discovered in 1924 but active mining started five years later. Since 1936 production has been

large. The tungsten veins occur in phyllite and sandstone on top of a mountain, 540 meters above the sea level. On the southern foot of the mountain are two small exposures of sericitized granite prophyry. The veins strike east-west and are almost vertical. They are characterized by abundant orthoclase with zinnwaldite and by the scarcity of sulphides. Veins occur in a sheeted zone, 900 meters long from east to west and 150 meters wide. Within this zone there are some 50 parallel but discontinuous veins more than 10 cm. wide. They range up to 70 cm. wide, and have an aggregate width of about 13 meters.

There were a number of adits driven from each side of the mountain at different levels. The ore within fifty meters from the top of the mountain is almost exhausted. The vertical extent of the ore is unknown. The ore averages about 1.5 to 2 per cent $WO_3$.

*Pankushan.* The Pankushan deposit, first mined in 1922, has produced considerable tonnage. In recent years production has declined materially, chiefly because the native mines cannot cope with water. The district is reached only by trails. The highest peak in the mining area is about 1,150 meters above sea level, and about 900 meters above the adjacent valleys. No igneous rock exposures have been found nearer than 7 miles from the mining district. Ore veins occur in brown thick-bedded Devonian sand-

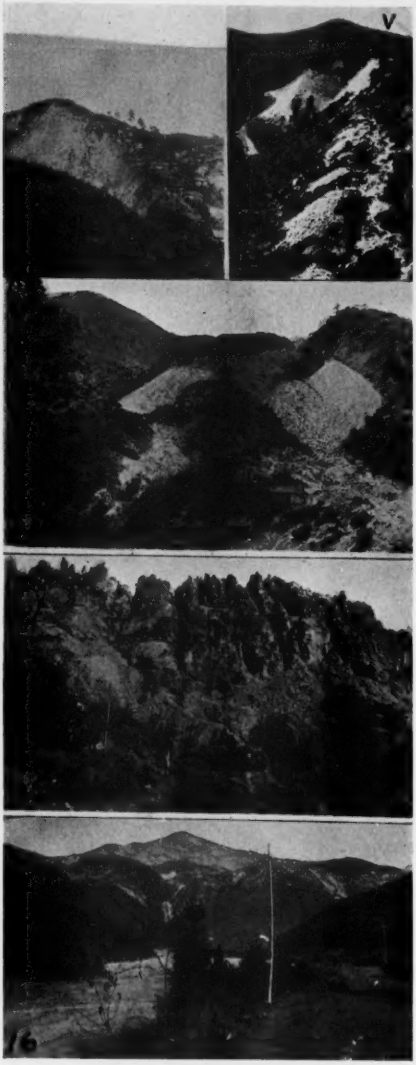
FIG. 12. Large wolframite-quartz vein (underground along the ridge) at Siaolung extends from the foot of a mountain to the top. It is mined along its outcrops by many short adits, driven from inside many of the houses.

FIG. 13. Wolframite-quartz vein in granite at Liunankeng, showing regularity and straightness of tungsten veins. The vein is mined along its outcrop.

FIG. 14. View of some open-pit mines at Hungshuichai. Pits are surrounded by white mining wastes.

FIG. 15. Closely-spaced, parallel tungsten veins on a ridge of Sihuashan, which are mined by open cuts, resulting in parallel trenches and cliffs.

FIG. 16. View of Sihuashan, showing the vast area covered by native mines. The mountain is colored white by mining wastes.




FIGS. 12–16.

stone which dips moderately southwestward. The veins strike N70°–80°W and dip 80° south, cutting the sandstone beds obliquely.

The main productive area is on the southern slope of the mountain, where a sheeted zone, 1,100 meters long from east to west and 250 meters wide, contains some twenty-one closely spaced veins, which are from 0.2 to 3.5 meter wide, and have an aggregate width of eleven meters. Some wide veins have been traced for 1,100 meters along the strike, but narrow veins are shorter. The veins are mined by a number of shafts. Deeper shafts reached a vertical depth of eighty meters. The vertical extent of workable ore seems to be great. The tungsten ore here is of high grade, one of the richest ores in Kiangsi. Some parts of veins consist almost entirely of wolframite. The ore contains a little more than 0.1 percent of bismuth sulphide and carbonate, which are recovered. Some small veins on the top of Pankushan contain more bismuth than tungsten.

*Siaolung.* This deposit was discovered in 1930. The tungsten veins occur in phyllite and quartzite. No granite exposure is known within several miles from the district.

In the main productive area, there are some 22 veins with an aggregate width of 7 meters, occurring in a sheeted zone of 300 meters in width. Seven out of the 22 veins are from one half to one meter wide. The veins extend vertically from one side of a mountain, across the ridge, to the other side of the mountain. They have been traced from 300 to 500 meters in length. The elevation difference between the lowest and the highest workings is 180 meters. There is no decrease in tenor of the ore in the deeper workings. The ore averages 2–2.5 per cent $WO_3$.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINNESOTA,
*May 10, 1943.*

# THE NATURE AND SIGNIFICANCE OF CERTAIN VARIATIONS IN COMPOSITION OF LOS ANGELES BASIN GROUNDWATERS.[1]

ROY R. MORSE.[2]

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[1] Presented before the Society of Economic Geologists at its Annual Meeting, held in conjunction with the A. I. M. E., at New York, February 15–17, 1943.

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ABSTRACT.

Comparison of a large number of analyses of Los Angeles Basin groundwaters shows the presence of several distinctive types, and indicates that different processes of varying importance operate to produce chemical variation here. The occurrence and general relationships of these water types are discussed, and evidence concerning certain processes of modification indicated.[3]

## GENERAL HYDROLOGICAL FEATURES.

As far as the artesian horizons of the water wells are concerned, the plains region southeast of Los Angeles may be considered structurally as a broad, spoon-shaped depression, with the southwest lip of the spoon reaching the sea south of Long Beach. Twenty miles to the north the San Gabriel and Los Angeles Rivers enter the basin near the handle of the spoon. On the southeastern rim the Santa Ana River contributes materially. These streams constitute the chief sources of groundwater replenishment.

The western rim of the basin north of Long Beach is determined by the structural elevation involved in the folding, faulting and tilting of the strata east of the Inglewood fault zone. South of Long Beach this elevated belt continues as the "coastal uplift" upon which occurs the series of faulted domes represented by the Long Beach, Seal Beach and Huntington Beach oil fields. On the south, east and northeast the basin is encircled by the San Joaquin, Coyote and Puente Hills uplifts where marine Miocene, Pliocene and Pleistocene strata outcrop extensively. These pass basinward beneath a thin mantle of nearly horizontal Recent and late Pleistocene marine and fluviatile deposits which effectively conceal the older strata over the entire artesian plain. Most of the water wells produce from the upper part of the Pleistocene. At scattered localities a warm water marine fauna, commonly interpreted as Upper San Pedro, has been recovered from well cuttings from depths ranging down to around 1,300 feet. As the coastal uplift is approached the Pleistocene section thins, so that along the south-

[3] Most of the water samples discussed were collected in the field by Mr. Frank Carter, and analyzed in the Shell Company refinery at Wilmington by Mr. E. S. Pickett. The writer is indebted to both for painstaking care and attention in these essential details, and to the Shell Oil Company for full cooperation in the study.

west margin of the artesian area the deeper wells reach aquifers of Lower San Pedro not usually reached by water wells in the central basin area.

The character of the sediments through which the artesian groundwaters circulate is of importance in this study. Nearly 40 years ago Mendenhall wrote of the area as follows (1)[4]:

> The coastal plain [5] is underlain by a succession of sand, gravel and clay beds whose constituent materials were transported to their present position by Santa Ana, San Gabriel, and Los Angeles Rivers, and perhaps in small part by the waves and currents of the Pacific. This plain represents a former wide bay which was gradually filled by alluvial debris that has been redistributed, in part at least, by oceanic waters as beach sands and gravel. Convincing evidence of this factor in distribution is furnished by the recent marine shells which are so often found in deep and shallow wells and on the present surface some miles from the shore line.

That the sea extended in Pleistocene time to points now far inland is shown by outcrops around the northern and eastern margins of the artesian area, and as is outlined below, by the occurrence of marine San Pedro faunas in water wells scattered widely over the basin. An upper and lower division of the San Pedro Pleistocene was early recognized by Arnold (3) on the following grounds:

> The upper San Pedro series is separated from the lower for three reasons: (1) on account of the unconformity existing between the two; (2) on account of the difference in their lithologic characters, the former consisting of gravels or coarse sands, while the latter is made up wholly of rather fine gray sands; and (3) because of the great difference in the faunas of the two; that of the former being one indigenous to warm water; that of the latter, one which is now found living where subboreal conditions prevail.

Unfortunately Arnold's type section was located on the coast where the section is thin. Proceeding inland the unconformity mentioned either disappears or becomes too faint to be recognized

[4] Numbers in parentheses refer to references listed at end of article.

[5] The term "coastal plain" refers to the general area herein termed "Los Angeles Basin," of which the "artesian area" may be said to constitute about two-thirds, the remainder being represented by the narrow marginal non-artesian belt. (R.R.M.)

in well sections; the lithologic distinction fails, since both members vary laterally in character; and the distinctive faunas are not always recovered in drilling operations. Thus it is not always clear which division of the San Pedro contributes to the water wells.

More recently Eckis (4) has emphasized the varied character of the Upper Pleistocene and Recent sediments outcropping around the inner margins of the artesian basin, pointing out that marine and continental members here interfinger. The latter appear to pass basinward into finer marine sediments but the entire section is characteristically arkosic in composition.

> In short, the petrology of these Upper Pleistocene Marine deposits is, in general, similar to that of the overlying Recent deposits of the present streams, and consequently it follows that the principal streams which deposit sediments upon the Coastal Plain today have been in existence throughout the accumulation of Upper Pleistocene deposits and were the chief contributors to the marine deposits (5).

Since Arnold wrote various names have been locally applied to certain marginal Pleistocene members, and disagreement exists regarding the subdivision of the Post-Pliocene. The problem of precise correlation is not here relevant. Over the past twenty years the writer has accumulated numerous identifications of marine Pleistocene collections of shells recovered in well drilling operations scattered over the basin, most of which were distinguished primarily on Arnold's original faunal criteria.[6] Accord-

[6] Personal communications of various dates, J. P. Smith, A. J. Tieje, Alex Clark, G. E. Miller. As demonstrating the wide extent of the marine Pleistocene here the following are some of the more significant. (1) *Along the coastal uplift:* "Marine San Pedro" in the outcrops and at shallow depths in the Baldwin Hills north of Inglewood, and at the other extremity of the basin at Huntington Beach; at Dominguez Hill "Lower or Upper San Pedro" at 200 ft.; at Seal Beach "probable Lower San Pedro" at 485 ft. (2) *In the central basin area:* "Undoubted Pleistocene, almost surely Upper San Pedro" from shallow wells near Artesia and at scattered localities over the plain around Wintersburg; at Los Alamitos in core from wildcat test at around 3000 ft. "probable San Pedro" microfauna; at Carmenita "Upper San Pedro" from similar core sample at 1200 ft.; near Santa Ana a "San Pedro" microfauna from a core at 2794 ft. (3) *On eastern margin* of the basin: Out-crops in Coyote Hills, gray arkose sands and gravels of San Pedro lithology carrying faunas of "Upper or Lower San Pedro" and of "Lower San Pedro by

ingly the older usage of terms will here be followed, recognizing that the "Upper San Pedro" includes thin marginal non-marine members; that the "Lower San Pedro" is not of lowermost Pleistocene age; and that the underlying "Fernando" includes at its top some beds of the lowermost Pleistocene.

What is of importance in the present discussion is the evidence that the marine facies of the San Pedro has a wide distribution throughout the artesian area, and that the Pleistocene section from which the wells produce is chiefly this facies, including extensive bodies of arkose sands interbedded with silts and clays chiefly of marine origin; and that where non-marine members occur they are of limited lateral extent and mineralogically similar to the marine.

With the structural barrier along the coastal rim and extensive clayey deposits flooring the artesian plain, ideal conditions for groundwater accumulation under head are afforded and widespread artesian conditions prevail, extending up-structure along the coastal margin nearly or quite to the crests of the local domes, and in the shallow sags between reaching practically to the sea. Mendenhall outlined the artesian area in 1903. The draw-down since that date has somewhat reduced this area, but in the general sense herein used the "artesian area" conforms to that shown by Mendenhall (Fig. 1).

Mendenhall (2) made numerous measurements of total solids in water wells scattered over the plain, and concluded that the course of the underground circulation is simple:

> the waters which come out through the Paso de Bartola spread into a broad stream, unite with those of the Los Angeles and Santa Ana systems, and seek an outlet to the ocean in the region between Los Alamitos Beach and Newport Beach . . . shallow wells, even in the areas of generally pure water, often contain very notable amounts of alkalies and . . . deeper wells generally carry a smaller proportion of salts than the shal-

ordinary rules of comparison"; on Bastanchury Ranch nearby from water wells at around 500 ft. "good marine fauna, San Pedro probably Upper." (4) *On northern margin* at Bell "marine Upper San Pedro" in water wells at 531–542 ft. and nearby a similar fauna reported by Arnold at 920–1320 ft.; in wells one mile and 3 miles east of Bell "Upper San Pedro" at 270 and 275 ft. respectively; 2 miles north of Bell a microfauna "Lower San Pedro or uppermost Fernando" at 1200 ft.

lower ones. The zones . . . illustrate well the effect of the runoff from the shale hills upon the waters in the adjacent lowlands, and show also the greater purity of the groundwaters in the zones of freest underground circulation.

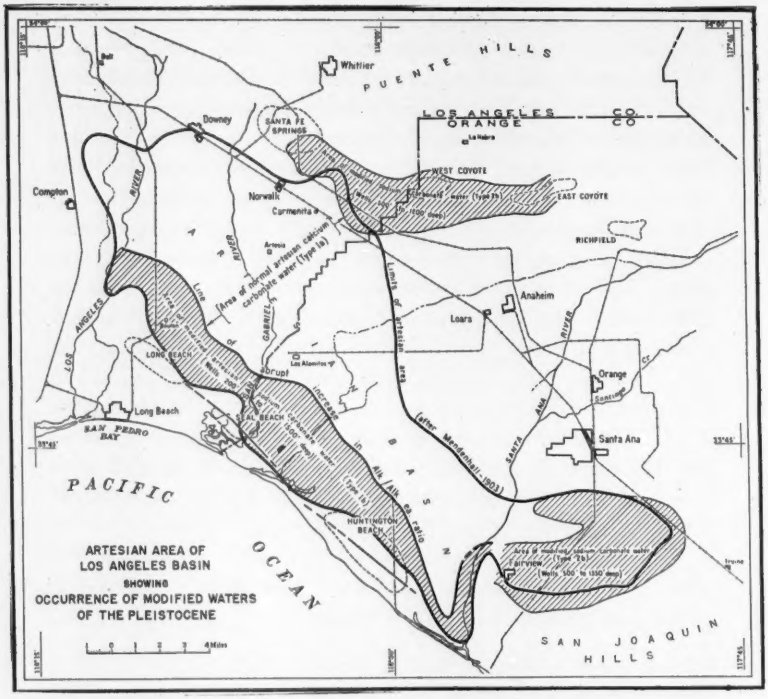


FIG. 1. Index map showing artesian area of Los Angeles Basin and occurrence of modified waters in the Pleistocene.

The analyses here discussed shed more light upon the nature of these chemical variations. The "notable amounts of alkalies" are of particular interest. The deeper waters are less concentrated than the shallower in certain districts only. In non-artesian areas the reverse is often the case. The "purest" waters encountered in the present study possess the highest proportion of alkalies.

These are found not necessarily in the regions of freest circulation; in the water wells of the artesian area they are restricted in occurrence to the southwestern margins on the flank of the coastal uplift. The chief purpose of this paper is to develop the evidence as to the real source of the chemical variations in these groundwaters and the reasons for their peculiar distribution.

## GENERAL CLASSIFICATION OF THE WATERS.[7]

The water samples here discussed come from wells of several kinds and various depths, and corresponding chemical differences occur, as reflected in the general classification scheme summarized below:

*Meteoric Waters*

1. *Artesian Strain*
   - Type 1a. Normal Calcium Carbonate Water
   - Type 1b. Modified Sodium Carbonate Water
2. *Non-Artesian Strain*
   - Type 2a. Normal Calcium Carbonate Water
   - Type 2b. Modified Sodium Carbonate Water
3. *Marginal Runoff Strain*
   - Type 3. Marginal Saline Water

*Mixed and Modified Waters*

Alkaline Chloride Water of Intermediate Concentration

*Connate Waters*

4. *Chloride Waters found in and near the Oil Measures (Pre-Pleistocene Strain)*

[7] Analytical details and comparisons are herein presented chiefly in tabular form. Table 1 shows the average analysis for each of the major strains compared with surface runoff and ocean water. Characteristic analyses of each water type recognized, together with an average analysis calculated from a number chosen as typical, are given in Tables 2–7. The averages of the types are assembled for ease of comparison in Table 8. As averages may conceal important features apparent only from a study of the property *ranges* in a given group, the ranges of certain constituents and ratios for the several water types are shown in Table 9. Variation *trends* in the artesian waters are summarized in Table 10.

Type 4a. Alkaline Chloride Water of High Concentration

Type 4b. Saline Water of Very High Concentration

NATURE AND OCCURRENCE OF MAJOR WATER STRAINS.

The chemical relationships between these four principal strains are shown in the averages of Table 1. The contrast in acid ratios,

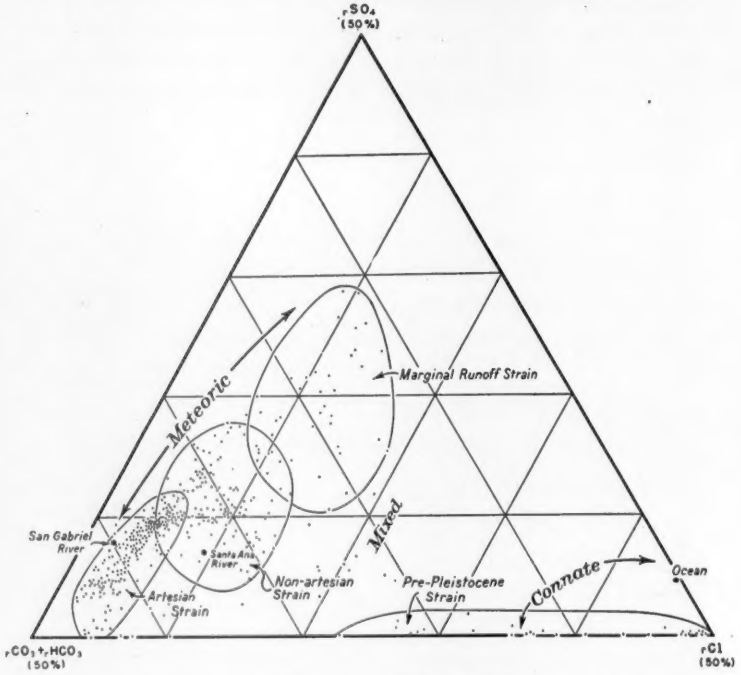


FIG. 2. Trilinear chart showing variations in acid ratios in Los Angeles Basin groundwaters (reacting values in per cent).

and the slight chemical overlapping of these groups, are shown graphically on the trilinear chart (Fig. 2). The significance of variations in base ratios is discussed beyond:

1. *The Artesian Strain* is represented by 196 samples in the cluster at the left corner of the trilinear chart. These typify the waters of the Pleistocene aquifers throughout the artesian area down to depths of 1,500 feet or more. The limits of occurrence practically coincide with Mendenhall's artesian limits curve (Fig. 1). These waters are characterized by very low total solids and relatively very high carbonate radicals, and consequently by very high alkalinity. A modified facies of more restricted occurrence is discussed beyond (type 1b).

2. *The Non-Artesian Strain* is typified by the 128 analyses of the intermediate cluster of meteoric waters on the diagram. Waters of this strain are found commonly over the Santa Ana alluvial fan in wells usually not over 500 feet deep, from its apex just below the Santa Ana gorge to the general vicinity of the artesian limits curve, where the strain merges chemically with waters of the artesian strain. Production here comes chiefly from Recent and Pleistocene fan material. Sporadically wells encounter this strain elsewhere just outside the artesian curve down to depths of around 1,000 feet where they clearly penetrate marine San Pedro sediments.

Water belonging chemically in the twilight zone between these two meteoric strains was found in scattered wells located just above the artesian limits curve around the northern edge of the artesian area as follows: in fifteen wells between the towns of Compton and Bell, producing from marine Upper San Pedro; in nine similar shallow wells in the general vicinity of the Santa Fe Springs field; in three wells in the La Habra syncline. A modified facies belonging to this strain (type 2b) was found in twenty-three wells producing from horizons lower in the San Pedro, at scattered localities around the eastern and southern margins of the basin. All occurrences of this general strain are non-artesian.

The waters of this strain are chemically of the same general character as those of the artesian strain but have about double the concentration, with higher sulphate, chloride and magnesium and lower carbonate radicals. They are typically neutral or weakly

saline in reaction character, except in the modified type, which is notably alkaline.

3. *The Marginal Runoff Strain* is an extreme facies of the meteoric group, illustrated by the 41 analyses of the upper and less compact cluster of the trilinear chart (Fig. 2). It was encountered in only two areas; in sixteen wells in the eastern foothills of the La Habra region from well depths ranging from 160 to 700 feet; in twenty-two wells along the edge of the plain southeast of Santa Ana and Irvine, ranging in depth between 100 and 1,600 feet. The wells penetrate Recent alluvial wash and underlying San Pedro strata. Both areas are in or adjacent to hilly regions in which pre-Pleistocene strata, including important areas of Miocene siliceous shales, are widely exposed. In both areas structural conditions are such as to somewhat restrict the underground circulation.

The water is more erratic in composition than the two preceding strains. It is definitely higher in rMg, $rSO_4$ and rCl. Total solids are double those of the average water of the Santa Ana cone, and increase definitely with depth (Tables 1 and 9). Secondary salinity[8] is persistent and strong. It seems likely that these samples reflect the contribution of materials picked up by the local runoff, where subsurface conditions are locally unfavorable for rapid merging with the general artesian circulation.

*Mixed and Modified Alkaline Chloride Waters of Intermediate Concentration.* Mention has been made of analyses which represent merging of artesian and non-artesian strains. Others occur which apparently bridge the gaps, chemically, between the "normal" and "modified" types. Still another group of mixed character is to be noted, intermediate between the altered meteoric and connate waters, as shown on the chart (Fig. 2). They are shown in Tables 8 and 9 for the sake of completeness but require no detailed discussion here.

4. *Chloride Waters of the Oil Measures.* The average deep-seated water encountered in and near the oil measures of the Los Angeles Basin is shown in Table 1. The strong contrast with the

[8] Using the convenient terminology of Palmer (6).

TABLE 1.

AVERAGE ANALYSES OF FOUR MAJOR LOS ANGELES BASIN WATERS AND COMPARISON WITH WATERS OF SAN GABRIEL AND SANTA ANA RIVERS AND OCEAN WATER

| | Meteoric Waters | | | | | Connate Waters | |
|---|---|---|---|---|---|---|---|
| | (1) Artesian Strain | San Gabriel River* at Rivera Sta. | (2) Non-Artesian Strain | Santa Ana River* at Corona Sta. | (3) Marginal Run-off Strain | (4) Pre-Pleistocene Strain | Ocean** (Challenger) Mean of |
| No. of Analyses Averaged... | 192 | 37 | 128 | 37 | 41 | 24 | 77 analyses |
| Reacting Values (%) | | | | | | | |
| rNa | 19.6 | 10.2 | 16.9 | 17.1 | 17.8 | 47.0 | 38.5 |
| rK | 1.0 | | | | 0.6 | | 0.8 |
| rCa | 23.4 | 29.2 | 24.8 | 24.4 | 19.9 | 1.8 | 1.8 |
| rMg | 6.0 | 10.6 | 8.3 | 8.5 | 11.7 | 1.2 | 8.9 |
| $rSO_4$ | 7.1 | 7.3 | 11.5 | 7.0 | 19.1 | 0.5 | 4.6 |
| rCl | 4.1 | 2.5 | 7.9 | 9.3 | 12.0 | 41.0 | 45.2 |
| $rCO_3$ | 0.6 | 0.8 | 29.8 | 1.0 | 17.9 | 8.5 | 0.2 |
| $rHCO_3$ | 38.0 | 39.1 | | 32.4 | | | |
| $rNO_3$ | 0.2 | 0.3 | 0.8 | 0.3 | 1.0 | — | — |
| Ratios[a] | | | | | | | |
| alk./ea.% | 41.2 | 20.4 | 33.8 | 34.2 | 36.8 | 94.0 | 78.6 |
| rNa/rK | 19.6 | ? | ? | ? | 29.6 | ? | 48.1 |
| rMg/rCa | .256 | .360 | .335 | .348 | .588 | .666 | 4.95 |
| Acid Ratio | .090 | .053 | .191 | .230 | .324 | 4.55 | 9.00 |
| rCarb./$rSO_4$ | 84.5 | 84.5 | 72.2 | 82.7 | 48.4 | 94.5 | 4.2 |
| Total Solids in p.p.m. | 267 | 246 | 410 | 347 | 865 | 14,096 | 35,000 |
| Water Horizons | Recent and San Pedro Pleistocene | Surface flow | Recent and San Pedro Pleistocene | Surface flow | Recent and San Pedro Pleistocene | Pliocene and Miocene Oil Measures | |

[a] In these tables the term "alk./ea.%" means per cent alkalis in alkalis plus alkaline earths in reacting values; the term "Acid Ratio" indicates the ratio $\frac{rCl}{rSO_4 + rCO_3 + rHCO_3}$; and the term "Carb./$SO_4$" or "Carbonate-Sulphate ratio" $= \frac{rCarb.}{rCarb. + rSO_4} \times 100$, where the factor "rCarb." $= rCO_3 + rHCO_3$ in per cent.

* San Gabriel River near Rivera, and Santa Ana River near Corona; mean of 37 analyses taken continuously during one year period (1907–1908). See U.S.G.S. Prof. Paper 135, pp. 142–144.

** Calculated from mean of 77 analyses. (Challenger Rpt., Physics and Chemistry, Vol. 1, p. 203. 1884.) See also Rogers, G. Sherbourne, U.S.G.S. Prof. Paper 117, p. 72. 1919.

TABLE 2.

NORMAL ARTESIAN CALCIUM CARBONATE WATER (TYPE 1*a*).

| Properties* | North-Central Basin Area | | | | | South-Central Basin Area | | | | Average of 148 typical | Surface Water | | Average of 105 Non-Artesian |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | 252 | 249 | 43 | 229 | 231 | 108 | 106 | 115 | 160 | | San Gabriel | Santa Ana | |
| Well Depths | 680′ | 800′ | 900′ | 750′ | 800′ | 1134′ | 532′ | 1100′ | 618′ | Type 1a | From Table 1 | | Type 2a |
| **Reacting Values (%)** | | | | | | | | | | | | | |
| rNa | 11.2 | 14.6 | 8.2 | 13.4 | 15.0 | 16.5 | 12.2 | 10.8 | 16.9 | 14.0 | 10.2 | 17.1 | 12.7 |
| rK | 0.7 | 0.5 | 1.4 | 1.1 | 0.7 | 0.7 | 1.1 | 1.0 | 0.5 | 1.0 | | | 1.0 |
| rCa | 29.5 | 27.3 | 28.9 | 29.2 | 29.9 | 24.9 | 28.9 | 30.7 | 25.7 | 27.7 | 29.2 | 24.4 | 27.4 |
| rMg | 8.6 | 7.6 | 11.5 | 6.3 | 4.4 | 7.9 | 7.8 | 7.5 | 6.9 | 7.3 | 10.6 | 8.5 | 8.9 |
| $rSO_4$ | 4.7 | 4.8 | 5.8 | 3.8 | 4.0 | 8.8 | 8.6 | 7.6 | 7.6 | 7.8 | 7.3 | 7.0 | 11.5 |
| rCl | 2.9 | 3.4 | 2.9 | 2.1 | 1.8 | 3.8 | 4.4 | 4.0 | 3.6 | 4.0 | 2.5 | 9.3 | 7.5 |
| $rCO_3$ | — | — | — | — | — | — | — | — | 2.7 | 38.0 | 0.8 | 1.0 | 30.0 |
| $rHCO_3$ | 42.2 | 41.6 | 41.1 | 44.1 | 44.0 | 37.1 | 36.7 | 38.2 | 35.9 | | 39.1 | 32.4 | |
| $rNO_3$ | 0.2 | 0.2 | 0.2 | — | 0.2 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 1.0 |
| **Ratios** | | | | | | | | | | | | | |
| alk./ea. % | 23.8 | 30.2 | 19.2 | 29.0 | 31.4 | 34.4 | 26.6 | 23.6 | 34.8 | 30.0 | 20.4 | 34.2 | 27.4 |
| rNa/rK | 16.0 | 29.2 | 5.9 | 12.2 | 21.4 | 23.6 | 11.1 | 10.8 | 33.8 | 14.0 | ? | ? | 12.7 |
| rMg/rCa | .29 | .28 | .39 | .22 | .15 | .32 | .26 | .24 | .26 | .26 | .36 | .35 | .32 |
| Acid Ratio | .06 | .07 | .06 | .04 | .04 | .08 | .10 | .09 | .08 | .09 | .05 | .23 | .18 |
| Carb./$SO_4$ | 90.0 | 89.7 | 87.6 | 92.1 | 91.7 | 80.8 | 81.0 | 83.4 | 83.5 | 83.0 | 84.5 | 82.7 | 72.3 |
| **Constituents in p.p.m.** | | | | | | | | | | | | | |
| Total Solids | 247 | 240 | 253 | 231 | 240 | 251 | 290 | 271 | 245 | 278 | 246 | 347 | 401 |
| $H_2S$ | 0.5 | 0.9 | 0.4 | 0.7 | 0.3 | 0.1 | 0.2 | — | 4.1 | 0.76 | | | 0.9 |
| Free $CO_2$ | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 0 | 3.0 | | | 4.4 |
| Na | 22.3 | 28.2 | 16.3 | 24.5 | 27.4 | 31.2 | 26.7 | 21.5 | 33.4 | | | | |
| K | 2.5 | 1.7 | 5.0 | 3.3 | 2.5 | 2.5 | 4.1 | 3.3 | 1.7 | | | | |
| Ca | 50.7 | 45.7 | 50.0 | 46.4 | 47.9 | 40.7 | 55.0 | 52.9 | 44.3 | | | | |
| Mg | 9.0 | 7.8 | 12.1 | 6.0 | 4.2 | 7.8 | 9.0 | 7.8 | 7.2 | | | | |
| $SO_4$ | 19.2 | 19.2 | 24.0 | 14.4 | 15.6 | 34.8 | 39.6 | 31.2 | 31.2 | | | | |
| Cl | 9.0 | 10.0 | 9.0 | 6.0 | 5.0 | 11.0 | 15.0 | 12.0 | 11.0 | | | | |
| $CO_3$ | — | — | — | — | — | — | — | — | 6.8 | | | | |
| $HCO_3$ | 222 | 213 | 106 | 213 | 213 | 186 | 213 | 203 | 188 | | | | |
| $NO_3$ | 1.0 | 1.0 | 1.0 | — | 1.0 | 1.0 | 2.0 | 1.0 | 1.0 | | | | |

* For abbreviations used in this column see explanation given in Table 1.

TABLE 3.

* For abbreviations used in this column see explanation given in Table 1.

TABLE 3.

MODIFIED ARTESIAN SODIUM CARBONATE WATER (TYPE 1*b*).

| Properties† | As Occurring in the Modified Belt of Southwest Margin | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Structurally High | | | | | | | | | Structurally Lower | | | | | | |
| Sample..... | 184 | 183 | 213 | 195 | 202 | 212 | 215 | 224 | Avg. 8 Samples | 141 | 200 | 209 | 208 | 201 | 199 | Avg. 6 Samples |
| Well Depths.. | 600′ | 1500′ | 600′ | 537′ | 1200′ | 800′ | 730′ | 849′ | 852′ | 558′ | 750′ | 900′ | 1026′ | 800′ | 750′ | 797′ |
| **Reacting Values (%)** | | | | | | | | | | | | | | | | |
| rNa | 42.7 | 40.7 | 44.3 | 43.4 | 42.9 | 43.4 | 44.7 | 39.5 | 42.7 | 37.3 | 42.3 | 44.1 | 40.9 | 42.1 | 42.4 | 41.5 |
| rK | 0.4 | 0.4 | 0.6 | 0.3 | 0.3 | 0.3 | 0.5 | 0.9 | 0.5 | 1.3 | 1.3 | 0.3 | 0.6 | 1.3 | 1.3 | 1.0 |
| rCa | 5.1 | 7.2 | 4.4 | 5.6 | 5.5 | 4.8 | 4.1 | 8.9 | 5.7 | 10.7 | 5.0 | 4.8 | 7.1 | 5.2 | 5.6 | 6.4 |
| rMg | 1.8 | 1.7 | 0.7 | 0.7 | 1.3 | 1.5 | 0.7 | 0.7 | 1.1 | 0.7 | 1.4 | 0.8 | 1.4 | 1.4 | 0.7 | 1.1 |
| $rSO_4$ | 0.2 | 3.9 | 1.4 | 1.3 | 3.9 | 4.8 | 2.1 | 4.2 | 2.7 | 6.4 | 7.3 | 7.1 | 8.1 | 7.5 | 6.8 | 7.2 |
| rCl | 3.8 | 4.1 | 3.9 | 4.8 | 4.8 | 4.2 | 4.8 | 3.9 | 4.3 | 4.0 | 4.3 | 4.2 | 4.0 | 4.4 | 4.5 | 4.2 |
| $rCO_3$ | — | 2.6 | 2.5 | — | 2.3 | 2.7 | 2.5 | — | 1.6 | 1.3 | 5.7 | 2.7 | 2.6 | 5.9 | 5.9 | 4.0 |
| $rHCO_3$ | 45.8 | 39.4 | 42.0 | 43.6 | 38.7 | 37.8 | 40.3 | 41.9 | 41.2 | 38.3 | 32.4 | 35.7 | 35.0 | 31.9 | 32.5 | 34.3 |
| $rNO_3$ | 0.2 | 0.0 | 0.2 | 0.3 | 0.3 | 0.5 | 0.3 | 0 | 0.2 | 0 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Ratios** | | | | | | | | | | | | | | | | |
| alk./ea. % | 86.2 | 82.2 | 89.8 | 87.4 | 86.4 | 87.4 | 90.4 | 80.8 | 86.4 | 77.2 | 87.2 | 88.8 | 83.0 | 86.8 | 87.4 | 85.0 |
| rNa/rK | 107.– | 102.– | 74.0 | 144.5 | 143.0 | 144.5 | 89.5 | 43.8 | 85.5 | 28.7 | 32.5 | 147.0 | 68.1 | 32.4 | 32.6 | 41.5 |
| rMg/rCa | .35 | .24 | .16 | .12 | .24 | .31 | .17 | .08 | .19 | .07 | .28 | .17 | .20 | .27 | .12 | .17 |
| Acid Ratio | .08 | .09 | .09 | .11 | .11 | .09 | .11 | .08 | .09 | .09 | .09 | .09 | .09 | .10 | .10 | .09 |
| Carb./$SO_4$ | 99.6 | 91.7 | 96.8 | 97.1 | 91.3 | 89.5 | 95.3 | 91.0 | 94.1 | 86.1 | 84.0 | 84.5 | 82.3 | 83.5 | 85.0 | 84.2 |
| **Constituents in p.p.m.** | | | | | | | | | | | | | | | | |
| T.S. | 329 | 261 | 214 | 223 | 230 | 203 | 212 | 216 | 236 | 211 | 212 | 202 | 210 | 212 | 210 | 210 |
| $H_2S$ | 5.1 | 2.9 | 2.8 | 5.7 | 4.3 | 2.6 | 4.5 | 2.1 | 3.8 | 1.0 | 2.8 | 1.8 | 1.9 | 3.4 | 3.4 | 2.4 |
| Free $CO_2$ | — | — | — | — | — | — | — | 2 | — | — | — | — | — | — | — | — |
| Na | 109.1 | 83.8 | 74.2 | 76.4 | 76.4 | 66.8 | 73.4 | 65.3 | | 60.1 | 69.7 | 67.5 | 66.0 | 67.5 | 67.5 | |
| K | 1.7 | 1.7 | 1.7 | 0.8 | 0.8 | 0.8 | 1.7 | 2.5 | | 3.3 | 3.3 | 0.8 | 1.7 | 3.3 | 3.3 | |
| Ca | 11.4 | 12.9 | 6.4 | 8.6 | 8.6 | 6.4 | 5.7 | 12.9 | | 15.0 | 7.1 | 6.4 | 10.0 | 7.1 | 7.9 | |
| Mg | 2.4 | 1.8 | 0.6 | 0.6 | 1.2 | 1.2 | 0.6 | 0.6 | | 0.6 | 1.2 | 0.6 | 1.2 | 1.2 | 0.6 | |
| $SO_4$ | 1.2 | 16.8 | 4.8 | 4.8 | 14.4 | 15.6 | 7.2 | 14.4 | | 21.6 | 25.2 | 22.8 | 27.6 | 25.2 | 22.8 | |
| Cl | 15.0 | 13.0 | 10.0 | 13.0 | 13.0 | 10.0 | 12.0 | 10.0 | | 10.0 | 11.0 | 10.0 | 10.0 | 11.0 | 11.0 | |
| $CO_3$ | 0 | 6.8 | 5.4 | 0 | 5.4 | 5.4 | 5.4 | 0 | | 27 | 12.3 | 5.4 | 5.4 | 12.3 | 12.3 | |
| $HCO_3$ | 310 | 105 | 186 | 202 | 183 | 155 | 175 | 183 | | 164 | 141 | 144 | 150 | 135 | 138 | |
| $NO_3$ | 1 | 0 | 1 | 1 | 1 | 2 | 1 | 0 | | 0 | 1 | 1 | 1 | 1 | 1 | |

† For abbreviations used in this column see explanation given in Table 1.

* Calculated and corrected for those reporting rNa and rK together.

TABLE 3—*Continued.*

| Properties | Typical "Profiles" on the Flank of the Coastal Uplift | | | | | | | | | | | | | Grouped Averages of the Type | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Huntington Beach | | | | | Bolsa Chica | | | | Seal Beach | | | | | | | |
| Sample..... | 140 | 144 | 197 | 191 | 193 | 207 | 199 | 200 | 204 | 114 | LASp. | 212 | 213 | Avg. 36 typical | Chiefly Upper San Pedro Avg. 6 | Lower San Pedro Avg. 11 | Bouton Facies I Avg. 10 from Table 4 |
| Well Depths.. | 500′ | 500′ | 516′ | 500′ | 280′ | 750′ | 750′ | 750′ | 980′ | 903′ | 712′ | 800′ | 600′ | | | | |
| Reacting Values (%) | | | | | | | | | | | | | | | | | |
| rNa | 18.4 | 34.8 | 36.0 | 36.2 | 40.6 | 22.5 | 42.4 | 42.3 | 44.8 | 39.5 | 36.1 | 43.4 | 44.3 | 41.5 | 41.5 | 43.1 | 40.9 |
| rK | 1.6 | 0.6 | 0.3 | 0.9 | 1.2 | 1.4 | 1.3 | 1.3 | 0.3 | 1.9 | 3.6 | 0.3 | 0.6 | 0.8 | 1.0 | 0.8* | 0.6 |
| rCa | 22.2 | 13.3 | 13.0 | 12.9 | 5.6 | 22.1 | 5.6 | 5.0 | 3.5 | 7.2 | 8.9 | 4.8 | 4.4 | 6.6 | 6.4 | 4.8 | 6.1 |
| rMg | 7.8 | 1.3 | 0.7 | ? | 2.6 | 4.0 | 0.7 | 1.4 | 1.4 | 1.4 | 1.4 | 1.5 | 0.7 | 1.1 | 1.1 | 1.5 | 2.4 |
| $rSO_4$ | 8.2 | 8.7 | 7.0 | 6.1 | 2.6 | 7.9 | 6.8 | 7.3 | 2.1 | 10.4 | 9.1 | 4.8 | 1.4 | 4.9 | 7.2 | 2.9 | 2.0 |
| rCl | 5.9 | 4.1 | 4.3 | 4.5 | 4.4 | 4.5 | 4.5 | 4.3 | 4.4 | 4.0 | 4.3 | 4.2 | 3.9 | 4.4 | 4.2 | 6.9 | 9.1 |
| $rCO_3$ | 0.7 | 0.7 | 1.3 | 3.3 | 1.8 | — | 5.9 | 5.7 | 2.5 | 2.0 | 3.2 | 2.7 | 2.5 | 3.5 | 4.0 | 5.4 | 1.1 |
| $rHCO_3$ | 34.9 | 36.5 | 37.1 | 36.1 | 41.2 | 37.3 | 32.5 | 32.4 | 40.7 | 33.6 | 33.0 | 37.8 | 42.0 | 37.0 | 34.3 | 34.7 | 37.6 |
| $rNO_3$ | 0.3 | 0 | 0.3 | 0 | 0 | 0.3 | 0.3 | 0.3 | 0.3 | 0 | 0.4 | 0.5 | 0.2 | 0.2 | 0.3 | 0.1 | 0.2 |
| Ratios | | | | | | | | | | | | | | | | | |
| alk./ea. % | 40.0 | 70.8 | 72.6 | 74.2 | 83.6 | 47.8 | 87.4 | 87.2 | 90.2 | 82.8 | 79.4 | 87.4 | 89.8 | 84.6 | 85.0 | 87.4* | 83.0 |
| rNa/rK | 11.5 | 58.0 | 120.0 | 40.2 | 33.8 | 16.1 | 32.6 | 32.5 | 160.0 | 20.8 | 10.0 | 144.5 | 74.0 | 52.0 | 41.5 | 54.0* | 68.2 |
| rMg/rCa | .35 | .10 | .05 | ? | .47 | .18 | .12 | .28 | .40 | .19 | .16 | .31 | .16 | .17 | .17 | .31 | .39 |
| Acid Ratio | .13 | .09 | .09 | .10 | .10 | .10 | .10 | .09 | .10 | .09 | .09 | .09 | .09 | .10 | .09 | .16 | .22 |
| Carb./$SO_4$ | 81.4 | 81.0 | 84.5 | 86.6 | 94.5 | 82.4 | 85.0 | 84.0 | 95.5 | 77.4 | 79.8 | 89.5 | 96.8 | 89.2 | 84.2 | 93.2 | 95.0 |
| Constituents in p.p.m. | | | | | | | | | | | | | | | | | |
| T.S. | 172 | 207 | 212 | 210 | 222 | 221 | 210 | 212 | 219 | 231 | 220 | 203 | 214 | 230 | 210 | 294 | 295 |
| $H_2S$ | 0 | 0.4 | 2.7 | 2.2 | 9.4 | 0 | 3.4 | 2.8 | 3.9 | 0.6 | 1.4 | 2.6 | 2.8 | 3.2 | 2.4 | 2.6 | 3.4 |
| Free $CO_2$ | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 0.6 |
| Na | 24.5 | 60.1 | 59.3 | 57.9 | 72.0 | 39.3 | 67.5 | 69.7 | 73.4 | 63.1 | 59.3 | 66.8 | 74.2 | | | | |
| K | 3.3 | 1.7 | 0.8 | 2.5 | 3.3 | 4.1 | 3.3 | 3.3 | 0.8 | 5.0 | 10.0 | 0.8 | 1.7 | | | | |
| Ca | 25.7 | 20.0 | 18.6 | 17.9 | 8.6 | 33.6 | 7.9 | 7.1 | 5.0 | 10.0 | 12.9 | 6.4 | 6.4 | | | | |
| Mg | 5.4 | 1.2 | 0.6 | 0 | 2.4 | 3.6 | 0.6 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 0.6 | | | | |
| $SO_4$ | 22.8 | 31.2 | 24.0 | 20.4 | 9.6 | 28.8 | 22.8 | 25.2 | 7.2 | 34.8 | 31.2 | 15.6 | 4.8 | | | | |
| Cl | 12.0 | 11.0 | 11.0 | 11.0 | 12.0 | 12.0 | 11.0 | 11.0 | 11.0 | 10.0 | 11.0 | 10.0 | 10.0 | | | | |
| $CO_3$ | 1.4 | 1.4 | 2.7 | 6.8 | 4.1 | — | 12.3 | 12.3 | 5.4 | 4.1 | 6.8 | 5.4 | 5.4 | | | | |
| $HCO_3$ | 122 | 166 | 161 | 152 | 191 | 172 | 138 | 141 | 177 | 141 | 144 | 155 | 186 | | | | |
| $NO_3$ | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 2 | 2 | 1 | | | | |

TABLE 4.

## TABLE 4.

MODIFIED ARTESIAN SODIUM CARBONATE WATER (TYPE 1B).

*(Unusually Deep for the Type or Otherwise Abnormal)*

| Properties* | Chemically Normal | | | | Bouton Facies—Chemically Somewhat Abnormal | | | | | | | | | | Bouton Facies Avg. of 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Off the Coastal Uplift | | | | Off Coastal Uplift | | | | On Coastal Uplift | | | | | | |
| Sample | 164 | 164-A | 327 | Lewellyn | Reyes No. 27 | 398 | 304 | 325 | 235 | 236 | 237 | 239 | 240 | 268 | |
| Well Depths | 500–2900′ | 2900′ | 680′ | 3288′ | 1000′ | 479′ | 1100′ | 510′ | 1200′ | 1500′ | 1500′ | 1100′ | 1200′ | 1100′ | 1069′ |
| **Reacting Values (%)** | | | | | | | | | | | | | | | |
| rNa | 38.4 | 47.2 | 45.4 | 46.6 | 40.3 | 36.6 | 47.4 | 46.2 | 41.4 | 42.2 | 43.1 | 37.8 | 37.9 | 35.8 | 40.9 |
| rK | 0.3 | 0.2 | 0.5 | ? | 1.1 | — | 0.4 | 0.7 | 0.3 | 0.5 | 0.5 | 1.0 | 0.7 | 0.8 | 0.6 |
| rCa | 9.9 | 2.1 | 3.4 | 3.4 | 6.3 | 8.5 | 0.7 | 2.0 | 4.9 | 4.7 | 4.5 | 8.4 | 10.2 | 11.4 | 6.1 |
| rMg | 1.4 | 0.5 | 0.7 | ? | 2.3 | 4.9 | 1.5 | 1.1 | 3.4 | 2.6 | 1.9 | 2.8 | 1.2 | 2.0 | 2.4 |
| $rSO_4$ | 6.9 | 0.5 | 9.1 | 5.6 | 1.0 | 2.2 | 2.6 | 2.8 | 0 | 0 | 0 | 2.5 | 1.9 | 6.9 | 2.0 |
| rCl | 4.7 | 3.8 | 5.3 | 5.3 | 12.2 | 8.1 | 14.1 | 8.6 | 7.3 | 6.6 | 10.0 | 7.6 | 8.8 | 7.8 | 9.1 |
| $rCO_3$ | 3.2 | 1.4 | 2.4 | 39.1 | 0.8 | 0 | 5.8 | 4.1 | 0 | 0 | 0 | 0 | 0 | 0 | 1.1 |
| $rHCO_3$ | 35.2 | 44.1 | 33.2 | — | 35.9 | 39.7 | 27.3 | 34.5 | 42.4 | 43.1 | 39.8 | 39.6 | 39.1 | 35.0 | 37.6 |
| $rNO_3$ | 0 | 0.2 | 0 | — | 0.1 | 0 | 0.2 | 0 | 0.3 | 0.3 | 0.2 | 0.3 | 0.2 | 0.3 | 0.2 |
| **Ratios** | | | | | | | | | | | | | | | |
| alk./ea. % | 77.4 | 94.8 | 91.8 | 93.2 | 82.8 | 73.2 | 95.6 | 93.8 | 83.4 | 85.4 | 87.2 | 77.6 | 77.2 | 73.2 | 83.0 |
| rNa/rK | 128.0 | 236.0 | 90.8 | ? | 36.6 | ? | 118.5 | 66.1 | 138.0 | 84.5 | 86.2 | 37.8 | 54.2 | 44.8 | 68.2 |
| rMg/rCa | .14 | .24 | .21 | ? | .37 | .58 | 2.14 | .55 | .69 | .55 | .42 | .33 | .12 | .18 | .39 |
| Acid Ratio | .10 | .08 | .12 | .12 | .32 | .19 | .40 | .21 | .17 | .15 | .25 | .18 | .21 | .19 | .22 |
| Carb./$SO_4$ | 84.8 | 98.8 | 79.7 | 87.5 | 97.4 | 94.7 | 92.8 | 93.2 | 100 | 100 | 100 | 94.1 | 95.2 | 83.5 | 95.0 |
| **Constituents in p.p.m.** | | | | | | | | | | | | | | | |
| Total Solids | 215 | 316 | 228 | 277 | 506 | 392 | 304 | 275 | 228 | 248 | 244 | 271 | 243 | 235 | 295 |
| $H_2S$ | 3.5 | 6.8 | 1.9 | — | — | — | 6.3 | 4.7 | 5.5 | 6.1 | 5.2 | 3.6 | 1.5 | 1.6 | 3.4 |
| Free $CO_2$ | 0 | 0 | 0 | — | — | — | — | — | 0 | 0 | 0 | 2 | 2 | 2 | 0.6 |
| Na | 63.8 | 111.3 | 77.2 | 85.4 | | 85.3 | 112.0 | 94.2 | 70.5 | 74.9 | 78.6 | 77.9 | 70.5 | 62.3 | |
| K | 0.8 | 0.8 | 1.7 | ? | | — | 1.7 | 2.5 | 0.8 | 1.7 | 1.7 | 3.3 | 2.5 | 2.5 | |
| Ca | 14.3 | 4.3 | 5.0 | 5.4 | | 17.2 | 1.4 | 3.6 | 7.1 | 7.1 | 7.1 | 15.0 | 16.4 | 17.1 | |
| Mg | 1.2 | 0.6 | 0.6 | ? | | 6.0 | 1.8 | 1.2 | 3.0 | 2.4 | 1.8 | 3.0 | 1.2 | 1.8 | |
| $SO_4$ | 24.0 | 2.4 | 32.4 | 21.6 | | 10.8 | 13.2 | 12.0 | 0 | 0 | 0 | 10.8 | 7.2 | 25.2 | |
| Cl | 12.0 | 14.0 | 14.0 | 15.0 | | 29.0 | 51.0 | 27.0 | 19.0 | 18.0 | 28.0 | 24.0 | 25.0 | 21.0 | |
| $CO_3$ | 6.8 | 4.1 | 5.4 | 93.6 | | 0 | 17.7 | 10.9 | 0 | 0 | 0 | 0 | 0 | 0 | |
| $HCO_3$ | 155 | 274 | 150 | — | | 244 | 172 | 186 | 191 | 202 | 191 | 216 | 191 | 161 | |
| $NO_3$ | 0 | 1.0 | — | — | | — | 1.0 | 0 | 0 | 1.0 | 1.0 | 2.0 | 1.0 | 1.0 | |

* For abbreviations used in this column see explanation given in Table 1.

TABLE 5.

NON-ARTESIAN MARGINAL SALINE WATERS.

| Properties* | Normal Calcium Carbonate Water (Type 2a) (N W)—Across Lower Santa Ana Cone—(S E) | | | | | | | | | Saline Water of the Runoff Strain (Type 3) Grouped as to Range in Total Solids | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg. of 105 typical | Low | Moderate | | High | Very High | Avg. of 41 typical |
| Sample† | 27 | 69 | 60 | 83 | 130 | 136 | 133 | 336 | | Avg. of 23 | Avg. of 6 | Avg. of 6 | Avg. of 9 | Avg. of 6 | |
| Well Depths | 1103′ | 480′ | 510′ | 410′ | 579′ | 200′ | 210′ | 208′ | 420′ | 510′ | 707′ | 573′ | 443′ | 925′ | Type 3 |
| **Reacting Values (%)** | | | | | | | | | | | | | | | |
| rNa | 17.8 | 17.0 | 12.5 | 13.0 | 10.1 | 12.1 | 9.4 | 11.0 | 12.7 | 15.3 | 20.5 | 17.8 | 17.6 | 23.6 | 17.8 |
| rK | 0.9 | 0.7 | 0.9 | 0.7 | 1.0 | 0.8 | 0.8 | 0.4 | 1.0 | 0.5 | 0.5 | 0.7 | 0.5 | 0.4 | 0.6 |
| rCa | 24.6 | 21.4 | 26.8 | 28.0 | 29.6 | 28.6 | 31.0 | 29.8 | 27.4 | 24.3 | 17.1 | 19.9 | 19.1 | 13.3 | 19.9 |
| rMg | 6.7 | 10.9 | 9.8 | 8.3 | 9.3 | 8.5 | 8.8 | 8.8 | 8.9 | 9.9 | 11.9 | 11.6 | 12.8 | 12.7 | 11.7 |
| $rSO_4$ | 13.8 | 17.5 | 9.6 | 9.9 | 10.3 | 11.7 | 8.3 | 12.4 | 11.5 | 12.6 | 18.6 | 18.1 | 20.9 | 22.7 | 19.1 |
| rCl | 5.8 | 6.1 | 4.8 | 8.6 | 7.6 | 7.2 | 9.2 | 8.6 | 7.5 | 14.0 | 12.1 | 14.3 | 12.9 | 13.0 | 12.0 |
| $rCO_3$ | — | — | — | — | — | — | — | — | } 30.0 | 22.2 | 18.8 | 16.5 | 14.9 | 13.8 | 17.9 |
| $rHCO_3$ | 30.2 | 26.1 | 35.3 | 30.8 | 31.6 | 30.0 | 30.8 | 27.7 | | | | | | | |
| $rNO_3$ | 0.2 | 0.3 | 0.3 | 0.7 | 0.5 | 1.1 | 1.7 | 1.3 | 1.0 | 1.2 | 0.5 | 1.0 | 1.3 | 0.5 | 1.0 |
| **Ratios** | | | | | | | | | | | | | | | |
| alk./ea. % | 37.4 | 35.4 | 26.8 | 27.4 | 22.4 | 25.8 | 20.4 | 22.8 | 27.4 | 31.6 | 42.0 | 37.0 | 36.2 | 48.0 | 36.8 |
| rNa/rK | 19.8 | 24.3 | 13.9 | 18.6 | 10.1 | 15.1 | 11.8 | 27.5 | 12.7 | 30.6 | 41.0 | 25.4 | 35.2 | 59.0 | 29.7 |
| rMg/rCa | .27 | .51 | .37 | .30 | .31 | .30 | .28 | .30 | .32 | .41 | .70 | .58 | .67 | .95 | .59 |
| Acid Ratio | .13 | .14 | .11 | .21 | .18 | .17 | .24 | .21 | .18 | .40 | .32 | .41 | .36 | .36 | .32 |
| Carb./$SO_4$ | 68.6 | 59.8 | 78.6 | 75.6 | 75.4 | 72.0 | 78.8 | 69.0 | 72.3 | 63.8 | 50.3 | 47.7 | 41.6 | 37.8 | 48.4 |
| **Constituents in p.p.m.** | | | | | | | | | | | | | | | |
| Total Solids | 295 | 492 | 302 | 395 | 354 | 407 | 459 | 447 | 401 | 616 | 781 | 870 | 1020 | 1291 | 865 |
| $H_2S$† | 0 | 0.6 | 0.2 | 0.8 | 0 | 0 | 0 | 0.9 | 0.9 | 1.3 | 15.3 | 1.3 | 0.9 | 0.7 | 2.8 |
| Free $CO_2$† | — | 8 | 4 | 4 | 4 | 6 | 4 | 4 | 4.4 | 4.6 | 5.3 | 4.8 | 4.3 | 9.0 | 5.3 |
| Na | 39.3 | 63.8 | 28.9 | 39.3 | 26.0 | 35.6 | 30.4 | 35.6 | | | | | | | |
| K | 3.3 | 4.1 | 3.3 | 3.3 | 4.1 | 4.1 | 4.1 | 2.5 | | | | | | | |
| Ca | 47.2 | 70.0 | 54.3 | 73.6 | 66.5 | 73.6 | 87.2 | 84.3 | | | | | | | |
| Mg | 7.8 | 21.7 | 12.1 | 13.3 | 12.7 | 13.3 | 15.1 | 15.1 | | | | | | | |
| $SO_4$ | 63.6 | 136.8 | 46.8 | 62.4 | 55.2 | 72.0 | 56.4 | 84.0 | | | | | | | |
| Cl | 20.0 | 35.0 | 17.0 | 40.0 | 30.0 | 33.0 | 46.0 | 43.0 | | | | | | | |
| $CO_3$ | — | — | — | — | — | — | — | — | | | | | | | |
| $HCO_3$ | 188 | 127 | 106 | 247 | 216 | 236 | 263 | 238 | | | | | | | |
| $NO_3$ | 1 | 4 | 2 | 6 | 4 | 9 | 15 | 12 | | | | | | | |

* For abbreviations used in this column see explanation given in Table 1.

† $H_2S$ and Free $CO_2$ not always determined. Averages shown are for those reporting.

TABLE 6.

† $H_2S$ and Free $CO_2$ not always determined. Averages shown are for those reporting.

TABLE 6.

MODIFIED NON-ARTESIAN SODIUM CARBONATE WATER (TYPE 2B).

| Properties* | Montebello Uplift | | | Santa Fe—Coyote Hills Uplift | | | | | | Southern Margin | | | | Average of 13 Typical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample† | 399 | C-34 | C-63 | 5 | 9 | 41-A | 385 | 89 | 355-C | 298 | 305 | 330 | 332 | |
| Well Depths | 335′ | ? | ? | 400′ | 700′ | 468′ | 730′ | 477′ | 700′ | 870′ | 1127′ | 1000′ | 960′ | 700′ |
| **Reacting Values (%)** | | | | | | | | | | | | | | |
| rNa | 35.9 | 42.0 | 41.9 | 21.6 | 37.7 | 34.8 | 42.4 | 39.5 | 42.3 | 32.7 | 37.3 | 36.1 | 36.0 | 38.3 |
| rK | ? | ? | ? | 12.2? | 0.8 | ? | 0.3 | 1.0 | ? | 0.8 | 0.6 | 1.5 | 0.6 | |
| rCa | 11.5 | 4.4 | 3.4 | 12.0 | 6.3 | 11.4 | 6.5 | 7.1 | 5.9 | 10.5 | 5.7 | 10.3 | 10.6 | 8.1 |
| rMg | 2.6 | 3.6 | 4.7 | 4.2 | 5.2 | 3.8 | 0.8 | 2.4 | 1.8 | 6.0 | 6.4 | 3.1 | 2.8 | 3.6 |
| $rSO_4$ | 5.4 | 4.8 | 4.1 | 8.6 | 11.9 | 11.0 | 11.4 | 11.1 | 15.5 | 13.4 | 10.1 | 12.6 | 13.0 | 10.2 |
| rCl | 13.2 | 12.6 | 13.1 | 12.2 | 13.4 | 8.6 | 8.9 | 10.1 | 9.2 | 6.9 | 12.5 | 4.9 | 5.5 | 10.1 |
| $rCO_3$ | — | — | — | — | 24.7 | — | 1.4 | — | — | — | 1.8 | 2.3 | — | 29.6 |
| $rHCO_3$ | 31.4 | 32.6 | 32.8 | 29.2 | — | 30.4 | 28.1 | 28.6 | 25.3 | 29.6 | 25.6 | 30.0 | 30.6 | |
| $rNO_3$ | — | — | — | — | — | — | 0.2 | 0.2 | — | 0.1 | — | 0.2 | 0.9 | 0.1 |
| **Ratios** | | | | | | | | | | | | | | |
| alk./ea. % | 71.8 | 84.0 | 83.8 | 67.6 | 77.0 | 69.6 | 85.4 | 81.0 | 84.6 | 67.0 | 75.8 | 73.2 | 73.2 | 76.6 |
| rNa/rK† | ? | ? | ? | ? | 47.2 | ? | 141.2 | 39.5 | ? | 40.8 | 62.1 | 72.2 | 60.0 | 56.9† |
| rMg/rCa | .23 | .82 | 1.38 | .35 | .83 | .33 | .12 | .34 | .31 | .57 | 1.12 | .30 | .26 | .44 |
| Acid Ratio | .37 | .34 | .35 | .32 | .37 | .21 | .22 | .25 | .22 | .16 | .33 | .11 | .13 | .25 |
| Carb./$SO_4$ | 85.4 | 87.2 | 89.0 | 77.2 | 67.6 | 73.3 | 72.2 | 72.1 | 62.0 | 68.9 | 73.1 | 72.0 | 70.1 | 74.4 |
| **Constituents in p.p.m.** | | | | | | | | | | | | | | |
| Total Solids | 293 | 480 | 573 | 634 | 555 | 595 | 585 | 397 | 553 | 567 | 293 | 242 | 224 | 461 |
| $H_2S$† | — | 0.7 | — | 4.0 | 11.6 | — | 1.4 | 1.0 | — | 0.5 | 1.6 | 1.1 | 1.1 | 2.5† |
| Free $CO_2$ | 0 | 0 | 0 | 0 | 0 | 22 | 0 | 4 | 18 | 9 | 0 | 0 | 0 | 4.1 |
| Na | 63.8 | 178 | 170 | 89.0 | 137.2 | 105.3 | 123.9 | 114.2 | 135.0 | 138.0 | 85.3 | 66.0 | 58.6 | |
| K | — | — | — | 8.5 | 5.0 | — | 1.7 | 5.0 | — | 5.8 | 2.5 | 1.7 | 1.7 | |
| Ca | 17.9 | 16 | 12 | 42.9 | 20.0 | 30.0 | 16.4 | 17.9 | 16.4 | 38.6 | 11.4 | 16.4 | 15.0 | |
| Mg | 2.4 | 8 | 10 | 9.0 | 9.6 | 6.0 | 1.2 | 3.6 | 3.0 | 13.3 | 7.8 | 3.0 | 2.4 | |
| $SO_4$ | 20.4 | 43 | 35 | 74.4 | 89.9 | 69.6 | 69.6 | 67.2 | 103.2 | 117.6 | 48.0 | 48.0 | 44.4 | |
| Cl | 36.0 | 82 | 82 | 77.0 | 75.0 | 40.0 | 40.0 | 45.0 | 45.0 | 45.0 | 44.0 | 14.0 | 14.0 | |
| $CO_3$ | — | — | — | — | — | — | 5.4 | — | — | — | 5.4 | 5.4 | — | |
| $HCO_3$ | 148 | 366 | 354 | 353 | 138 | 244 | 216 | 219 | 214 | 330 | 155 | 147 | 133 | |
| $NO_3$ | — | — | — | — | — | — | 1.0 | — | — | 1.0 | 0 | 1.0 | 4.0 | |

* For abbreviations used in this column see explanation given in Table 1.

† Averages determined from those reporting, omitting No. 5 in rNa/rK average as unreliable in K determination.

TABLE 7.

CHLORIDE WATERS FOUND IN AND NEAR THE OIL MEASURES (TYPES 4A–B).

| | Alkaline Chloride Water of High Concentration (Type 4a) | | | | | | | | | | | Saline Water of Very High Concentration (Type 4b) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field..... | | Whittier | | Santa Fe Springs | | | Brea | Richfield | East Coyote | Torr.-Redondo | Avg. 13 typical | Montebello | | Brea | Long Beach | Dominguez | Torrance | Inglewood | Avg. 11 typical |
| | Salt Lake | Edge | Field | Produced with Oil | | | | | | | | | | | | | | | |
| Depth or Zone.... | | -3727' | 4675–4762' | Foix | Bell | Meyer | Upper | Chapman | 11 Wells | Top Water | Type 4a | Shallow | Oil Zone | Lower | 15 Wells | 2 Wells Callender | Edge Oil Zone | 9 Wells Main | Type 4b |
| Reacting Values (%) | | | | | | | | | | | | | | | | | | | |
| rNa | 49.3 | 48.8 | 48.6 | 47.7 | 47.9 | 48.3 | 48.4 | 45.9 | 48.3 | 48.3 | 48.3 | 45.6 | 47.2 | 47.4 | 44.4 | 45.4 | 45.6 | 42.2 | 45.5 |
| rK | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| rCa | 0.3 | 0.5 | 0.9 | 1.1 | 0.5 | 0.5 | 0.8 | 3.6 | 0.6 | 0.9 | 0.9 | 4.4 | 1.3 | 1.2 | 2.9 | 3.8 | 2.4 | 2.8 | 2.8 |
| rMg | 0.3 | 0.7 | 0.3 | 1.2 | 1.6 | 1.1 | 0.8 | 0.4 | 1.1 | 0.8 | 0.8 | — | 1.5 | 1.2 | 2.7 | 1.2 | 1.9 | 4.9 | 1.7 |
| $rSO_4$ | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 1.1 | 0.2 | 0.1 | 0 | 0.1 | 0.5 | 0 | 0 | 0 | 0.15 | 0 | 0 | 1.0 |
| rCl | 38.5 | 36.3 | 48.1 | 27.8 | 22.6 | 45.1 | 26.3 | 37.4 | 36.6 | 40.7 | 35.8 | 46.3 | 48.2 | 48.9 | 48.8 | 49.2 | 48.1 | 47.7 | 47.0 |
| $rCO_3$ | 11.4 | 13.7 | 1.9 | — | 0.2 | 0.1 | 22.4 | — | 11.7 | 2.4 | 14.1 | 0.7 | 1.8 | 1.1 | 1.2 | 0.15 | 0 | 0 | 2.0 |
| $rHCO_3$ | | | | 22.0 | 27.2 | 4.7 | | 12.4 | | 6.9 | | — | — | | | | 1.9 | 2.3 | |
| Ratios | | | | | | | | | | | | | | | | | | | |
| alk./ea. | 98.6 | 97.6 | 97.6 | 95.4 | 95.8 | 96.6 | 96.8 | 91.8 | 96.6 | 96.6 | 96.6 | 91.2 | 94.4 | 94.8 | 88.8 | 90.8 | 91.2 | 84.4 | 91.0 |
| rMg/rCa | 1.0 | 1.4 | .33 | 1.1 | 3.2 | 2.2 | 1.0 | .11 | 1.8 | .89 | .89 | ? | 1.2 | 1.0 | .93 | .32 | .79 | 1.7 | .61 |
| Acid Ratio | 3.4 | 2.6 | 24.0 | 1.3 | .8 | 9.4 | 1.1 | 3.0 | 3.1 | 4.4 | 2.5 | 38.6 | 26.8 | 44.5 | 40.6 | 164. | 25.3 | 20.8 | 15.7 |
| Carb./$SO_4$ | 100 | 100 | 95.1 | 99.5 | 100 | 100 | 95.2 | 98.6 | 99.1 | 100 | 99.1 | 58.2 | 100 | 100 | 100 | 50 | 100 | 100 | 66.6 |
| Total Solids in p.p.m. | 16,548 | 3597 | 8768 | 5820 | 5640 | 10,645 | 6315 | 3449 | 9141 | 6733 | 7832 | 9580 | 25,608 | 16,914 | 27,786 | 25,701 | 29,040 | 35,165 | 20,516 |

TABLE 8.

COMPARISON OF AVERAGES OF TYPE AND INTERMEDIATE WATERS.

| | Meteoric Waters | | | | | | | | Connate Waters | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Artesian Strain | | | Non-Artesian Strain | | | Run-off Strain | Mixed and Modified Waters | Pre-Pleistocene Strain | |
| | Normal | Modified | | Normal | Modified | | Saline | | Alkaline | Saline |
| | Type 1a | Intermediate | Type 1b | Type 2a | Intermediate | Type 2b | Type 3 | | Type 4a | Type 4b |
| No. in Average | 148 (Table 2) | 8 | 36 (Table 3) | 105 (Table 5) | 11 | 13 (Table 6) | 41 (Table 5) | 12 | 13 (Table 7) | 11 (Table 7) |
| Reacting Values (%) | | | | | | | | | | |
| rNa | 14.0 | 25.0 | 41.5 | 12.7 | 24.8 | 38.3 | 17.8 | 47.8 | 48.3 | 45.5 |
| rK | 1.0 | 0.9 | 0.8 | 1.0 | 0.8 | | 0.6 | | | |
| rCa | 27.7 | 20.2 | 6.6 | 27.4 | 17.0 | 8.1 | 19.9 | 1.3 | 0.9 | 2.8 |
| rMg | 7.3 | 3.9 | 1.1 | 8.9 | 7.4 | 3.6 | 11.7 | 0.9 | 0.8 | 1.7 |
| $rSO_4$ | 7.8 | 5.3 | 4.9 | 11.5 | 11.8 | 10.2 | 19.1 | 5.2 | 0.1 | 1.0 |
| rCl | 4.0 | 3.8 | 4.4 | 7.5 | 8.9 | 10.1 | 12.0 | 21.1 | 35.8 | 47.0 |
| $rCO_3$ | 38.0 | 40.6 | 3.5 | 30.0 | 29.0 | 29.6 | 17.9 | 23.7 | 14.1 | 2.0 |
| $rHCO_3$ | | | 37.0 | | | | | | | |
| $rNO_3$ | 0.2 | 0.3 | 0.2 | 1.0 | 0.3 | 0.1 | 1.0 | 0 | | |
| Ratios | | | | | | | | | | |
| alk./ea. % | 30.0 | 51.8 | 84.6 | 27.4 | 51.2 | 76.6 | 36.8 | 95.6 | 96.6 | 91.0 |
| rNa/rK | 14.0 | 27.8 | 52.0 | 12.7 | 31.0 | 56.9 | 29.7 | 170.0 | ? | ? |
| rMg/rCa | .26 | .19 | .17 | .32 | .43 | .44 | .59 | .69 | .89 | .61 |
| Acid Ratio | .09 | .08 | .10 | .18 | .22 | .25 | .32 | .73 | 2.5 | 15.7 |
| Carb./$SO_4$ | 83.0 | 88.6 | 89.2 | 72.3 | 71.1 | 74.4 | 48.4 | 82.0 | 99.1 | 66.6 |
| Constituents in p.p.m. | | | | | | | | | | |
| Total Solids | 278 | 222 | 230 | 401 | 476 | 461 | 865 | 810 | 7,832 | 20,516 |
| $H_2S$ | 0.8 | 1.8 | 3.2 | 0.9 | 0.7 | 2.5 | 2.8 | 26.4 | ? | ? |
| Free $CO_2$ | 3.0 | 1.0 | 0 | 4.4 | 3.6 | 4.1 | 5.3 | 0 | 0 | 0 |

TABLE 9.

COMPARISON OF RANGES IN VALUES OF CERTAIN SIGNIFICANT PROPERTIES FOR ALL TYPES.

| | | | Artesian | | | Non-Artesian | | | Marginal Runoff | Mixed and Modified | Connate | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Normal Type 1a | Modified Intermediate | Modified Type 1b | Normal Type 2a | Modified Intermediate | Modified Type 2b | Type 3 | | Type 4a | Type 4b |
| Indicative of *Source* | Concentration (Total Solids in p.p.m.) | Range | 220–350 | 200–250 | 195–265 | 290–560 | 287–767 | 224–634 | 600–1100 | 366–1561 | 3400–11,500 | 9500–35,000 |
| | | Avg. | 278 | 222 | 230 | 401 | 476 | 461 | 865 | 810 | 7832 | 20,516 |
| | Chloride (rCl in %) | Range | 1.6–7.4 | 2.2–4.5 | 3.8–5.4 | 3.6–12.6 | 4.7–13.7 | 4.9–13.4 | 8.0–24.0 | 12.3–35.1 | 22.6–48.1 | 43.5–49.4 |
| | | Avg. | 4.0 | 3.8 | 4.4 | 7.5 | 8.9 | 10.1 | 12.0 | 21.1 | 35.8 | 47.0 |
| | Acid Ratio $\frac{rCl}{rSO_4+rCarb}$ | Range | .02–.18 | .04–.18 | .06–.13 | .10–.35 | .10–.38 | .11–.37 | 16.0–75.0 | .31–.78 | 1.26–24.0 | 20.7–164.0 |
| | | Avg. | .09 | .08 | .10 | .18 | .22 | .25 | .32 | .73 | 2.50 | 15.70 |
| | Sulphate ($rSO_4$ %) | Range | 3.1–12.5 | 3.6–9.0 | 0.2–10.4 | 6.3–18.5 | 4.9–16.9 | 4.1–15.5 | 2.0–29.0 | 0–14.7 | 0–1.1 | 0–0.5 |
| | | Avg. | 7.8 | 5.3 | 4.9 | 11.5 | 11.8 | 10.2 | 19.1 | 5.2 | 0.1 | 1.0 |
| | Carbonate (rCarb. %) | Range | 33–45 | 37–43 | 35–46 | 23–37 | 25–31 | 25–33 | 10–28 | 20–28 | 1.9–27.4 | 0.1–2.3 |
| | | Avg. | 38.0 | 40.6 | 40.5 | 30.0 | 29.0 | 29.6 | 17.9 | 23.7 | 14.1 | 2.0 |
| | Carb./$SO_4$ % | Range | 75–95 | 78–93 | 77–99 | 58–84 | 65–86 | 62–89 | 26–82 | 61–100 | 95–100 | 50–100 |
| | | Avg. | 83.0 | 88.6 | 89.2 | 72.3 | 71.1 | 74.4 | 48.4 | 82.0 | 99.1 | 66.6 |
| Indicative of *Alteration* | rMg/rCa | Range | .15–.40 | .10–.40 | .08–.50 | .14–.75 | .14–.72 | .23–1.38 | .15–.75 | .13–2.86 | .11–3.20 | .32–1.75 |
| | | Avg. | .26 | .19 | .17 | .32 | .43 | .44 | .59 | .69 | .89 | .61 |
| | Alk./Ea. % | Range | 18–50 | 44–62 | 71–91 | .15–.40 | 42–63 | 67–85 | 16–60 | 90–99 | 92–99 | 84–95 |
| | | Avg. | 30.0 | 51.8 | 84.6 | 27.4 | 51.2 | 76.6 | 36.8 | 95.6 | 96.6 | 91.0 |
| | rNa/rK | Range | 4–40 | 11–62 | 21–167 | 1–50 | 14–62 | 39–141 | 10–80 | 21–414 | ? | ? |
| | | Avg. | 14.0 | 27.8 | 52.0 | 12.7 | 31.0 | 56.9 | 29.7 | 170.0 | | |
| | $H_2S$ | Range | 1 | 0.8–2.7 | 0.4–5.7 | 0.2–2.5 | 0–1.4 | 0–11.6 | 0–94 | 0–112 | ? | ? |
| | | Avg. | 0.8 | 1.8 | 3.2 | 0.9 | 0.7 | 2.5 | 2.8 | 26.4 | | |
| | Free $CO_2$ | Range | 3–4 | 0–4 | None | 0–13 | 0–8 | 0–22 | 0–13 | None | 0 | 0 |
| | | Avg. | 3.0 | 1.0 | 0 | 4.4 | 3.6 | 4.1 | 5.3 | 0 | | |

TABLE 10.

TABLE 10.

VARIATION TRENDS IN ARTESIAN WATERS.*

| Properties† | Artesian Waters | Modified Artesian Waters (Type 1b) | | | | |
|---|---|---|---|---|---|---|
| | *Progressing from normal* to modified these show the following trends (See tables 8, 9) | Variations with Structural Position the Up-Structure Wells Show | | Var. with Inc. Depth at given (flank) structural position (Wells No. 141, 164–164A) (See tables 3, 4) | Variations with Stratig. Horizon Compd. with like type from Up. San Pedro | |
| | | (a) (by groups) (See table 3) | (b) (in 3 selected "profiles") (See table 3) | | (a) Lower San Pedro Water shows (See table 3) | (b) Bouton Facies Shows (See table 3) |
| Reacting Values (%) | | | | | | |
| rNa | + | +s | + | + | C | C |
| rK | −s | − | er | − | C | − |
| rCa | − | −s | − | − | −s | er |
| rMg | − | C | −er | er | +s | + |
| $rSO_4$ | −s(?) | − | − | − | − | − |
| rCl | C | C | C | C | + | + |
| rCarb | C | + | + | + | + | +er |
| T.S. in p.p.m. | −s(?) | + | +er | + | + | + |
| $H_2S$. in p.p.m. | + | + | + | + | C | + |
| Ratios† | | | | | | |
| alk./ea. % | + | +s | + | + | C | Cer |
| rNa/rK | + | + | +er | + | er | +er |
| rMg/rCa | −er | +er | er | + | + | + |
| Acid Ratio | C | C | C | C | + | + |
| Carb./$SO_4$ | +s(?) | + | + | + | + | + |

* Symbols used in this table have the following significance:

+ = pronounced increase
+s = definite but slight increase
− = pronounced decrease
−s = definite but slight decrease
C = practically constant
er = erratic values and trend uncertain.

† For abbreviations used in this column see explanation given in Table 1.

meteoric types is well shown on the trilinear diagram. In chloride and total solids analyses of this group more closely approach composition of sea water. As shown below two distinct but closely related types can be recognized, an upper alkaline and a lower saline type. Both are lower in $SO_4$ and Mg than sea water or any of the meteoric types. The rMg/rCa ratio is always more like the values found in the meteoric waters, whereas in sea water this ratio is five to eight times higher. The alk./alk.ea.[9] ratio is persistently much higher than in either sea water or the meteoric types.

*Alkaline Chloride Water* of high concentration occurs as an upper oil zone water in both Pliocene and Miocene strata, on both sides of the basin (type 4a, Tables 7–9). It is commonly followed in depth by the even more concentrated saline (type 4b). However, it is not restricted to the vicinity of oil pools, as is shown by two samples from a wildcat well in Puente Hills. The ions present are chiefly Na, Cl, and carbonate. High primary salinity (avg. 71 per cent), little or no secondary alkalinity and persistent primary alkalinity are the reaction characteristics. The water has an average concentration of about one-third that of its deeper saline relative, but from sixteen to thirty-five times that of the meteoric types listed, from which it is further distinguished by high primary salinity, erratic but higher rMg/rCa, and practical absence of $SO_4$. This water shows the highest values of all in alk./alk.ea. ratio and in rMg/rCa. Compared with sea water it has relatively less $SO_4$, Ca and Mg, and more carbonate.

*Saline Water* of very high concentration (type 4b) normally occurs lower in the oil measures, in the manner indicated in the last paragraph. This is almost a straight sodium chloride water, with slightly more Ca and Mg than the preceding type. Total solids range from near the maximum found in the latter, to values somewhat exceeding those of sea water. These analyses, together with those representing the marginal saline meteoric type, are the only ones which consistently show important secondary salinity.

[9] For definition of this and other ratios used in this discussion see footnote, Table 1.

*Summary.* As to the waters found in the Pleistocene and Recent beds the *artesian* are uniformly low in total solids and high in the proportion of carbonate radicals, whereas the *non-artesian* and runoff strains, more erratic in character and occurrence, show the effect of nearby outcrops in their higher total solids, particularly as to Mg, $SO_4$ and Cl radicals. The *chloride* waters of the Pliocene approach sea water in character but are much lower in Mg and $SO_4$ and higher in Na and carbonate.

From the nature and occurrence of these major strains it is clear that we are dealing with meteoric waters of obvious source, deeper-seated waters of more complicated history and of a character commonly classified as connate, and with various mixtures and modifications. We will confine ourselves chiefly in the following discussion to the subject of modification of the normal meteoric waters. It will be noted that contrasts in the acid radicals and total solids afforded the major grouping of the analyses in the above classification scheme. Comparison of the base radicals shows that within the general "strains" important modification in chemical composition occurs.

### NORMAL AND MODIFIED ARTESIAN CABONATE WATERS.

*Normal Calcium Carbonate Water* (*type 1a*). This is a very dilute lime carbonate water with predominant secondary alkalinity. Its character is shown by the typical analyses and the average of 148 samples of Table 2. This is the water normally encountered in Upper San Pedro aquifers throughout the artesian area down to the greatest depths commonly reached in water wells (1,200 to 1,500 feet). The ranges in values of constituents are narrow, indicating a regularity in composition to be expected only where groundwater circulation is comparatively unrestricted (see Table 9). This is a normal meteoric water of uniform concentration and widespread occurrence.

*Modified Sodium Carbonate Water* (*type 1b*). Artesian water of this extreme type is produced from San Pedro beds in shallow and deep wells in a belt along the flank of the coastal uplift three miles wide and eighteen miles long, extending along the southwest

edge of the artesian area from Dominguez Hill to southeast of Huntington Beach (Fig. 1). Thirty-six analyses were selected as typical and the average calculated as shown in Table 3. Individual analyses are grouped in the table according to structural position; the highest are from near the crest of the coastal uplift; those of lower structural position occur from one to two miles down the basinward flank. Unusually deep samples for the type (Table 4) include the Llewellyn sample from a wildcat well in the central part of the artesian area east of Long Beach, and two samples (164, 164–A) from different depth zones in a wildcat well nearer the coast two miles north of Huntington Beach.

The water of this type is of rather extreme but uniform composition and of restricted occurrence in the water wells. It is essentially a very dilute sodium carbonate water. The carbonate and chloride ranges (Table 9) are those of the normal lime carbonate water (type 1a), but the base ratios are in sharp contrast, the *alk./alk.ea. ratios being practically reversed.* The ratio rNa/rK is notably higher. Sulphate covers about the same *range* in each, though the *average* is somewhat lower in the altered type. The more noticeable $H_2S$ content, absence of free $CO_2$, and a persistent straw-yellow or brown discoloration further distinguish this type.

NORMAL AND MODIFIED NON-ARTESIAN CARBONATE WATERS.

*Normal Calcium Carbonate Water (type 2a).* This is a lime carbonate water much like the artesian type 1a. The proportions of the bases are strikingly similar (Tables 5, 8, 9). The contrast appears when we consider the acid radicals and total solids, this non-artesian type showing persistently higher rCl, $rSO_4$ and total solids, with a tendency to higher rMg/rCa ratio and free $CO_2$. Secondary salinity is an unfailing characteristic. As in other non-artesian waters, the properties cover a wider range in values than in the artesian.

This is the normal water of the wells on the Santa Ana cone down to the upper limits of the artesian area. It comes from

Recent and late Pleistocene beds which are in part at least non-marine. The few wells around the northern margins of the artesian area producing the waters with weak secondary salinity, which otherwise fall in either strain, produce from fossiliferous marine Upper San Pedro strata. Similar water of borderline character is encountered in wells in the La Habra and Irvine synclines, interspersed with wells producing the more extreme saline water of the runoff strain.

Apart from the study of modification we see from the distribution of the types so far reviewed that outside the artesian area the groundwaters contain more total solids. Near the uplifts bounding the basin on the north and east higher values occur in $rSO_4$, rCl and rMg giving marginal waters with secondary salinity and higher values in rMg/rCa. To this extent Mendenhall's idea of the effect of runoff and of greater "purity in regions of freest circulation" applies. However, the higher concentration represented by the extremes of the runoff strain (type 3) accompanies a general increase in well depths near the foothills, and conditions of more restricted circulation, so that greater purity is here not found at depth.

*Modified Sodium Carbonate Water (type 2b).* Table 6 lists thirteen analyses as typical. One is from a shallow well on the margin of the Montebello uplift; four occur in water wells in the Santa Fe Springs field; three are on the west and southwest flanks of the Coyote uplift; and four come from the southern margin of the basin south of Santa Ana. In each case the San Pedro is the chief source of production. In the wells at the southern margin some slight contribution from pre-San Pedro may occur.

This type differs from the unmodified water (type 2a) chiefly in the inversion of the alk./alk.ea. ratio and higher rNa/rK ratio, changes parallel with those found in the artesian strain. In fact, these properties are very similar in the two modified types (types 1b, 2b; Table 8). However, type 2b has on the average twice the total solids, $rSO_4$ and rCl, linking it chemically with the other waters of the non-artesian strain.

ORIGIN OF MODIFIED TYPES AND SIGNIFICANT VARIATIONS.

*Evidence of a Common Meteoric Origin.* In view of the simple artesian conditions and limited sources of supply we might expect uniformity in composition of the shallow groundwaters here. This is the case to a remarkable degree, as shown by the narrow ranges covered by the several properties throughout several hundred analyses from wells widely scattered over the basin (Table 9). The evidence shows that the *calcium* carbonate type is the *normal* water of the water wells throughout the area; that it has its widest extent in the shallower depths, in wells not over 300 feet deep actually reaching nearly to the sea between Huntington Beach and Newport; and that it extends to greatest depths in the central, deeper portion of the depression, where it reaches depths of 1,300 feet or more. It is the usual ground water of the Upper San Pedro beds, and its close chemical similarity to the river waters which continuously replenish these beds leaves no doubt as to its meteoric origin.

The artesian *sodium* carbonate water (type 1b) on the other hand, occurs *in the water wells* only along the southwest rim of the basin. It is found in both Upper and Lower San Pedro, but has widest extent in the lower beds. Again the narrow ranges of properties reflect a striking uniformity in composition. In all but $SO_4$, $H_2S$ and rNa/rK the property-ranges are the narrowest of all types. Moreover, the ranges of certain properties conform to those of the normal artesian water (type 1a) so closely that further argument as to identity of source seems superfluous. But for the inversion of the ratio of alkalies to alkaline earths the range in reaction characteristics of the normal and modified waters would be almost indistinguishable (Table 9).

Carbonate waters somewhat similar in reaction properties to these "modified" waters have often been noted in the vicinity of oil pools, and their origin variously explained. In these cases the origin of the carbonate has generally been in question. In the shallow waters of the Los Angeles Basin no problem is presented by the relatively high carbonate content found in and near the oil fields since an adequate source is at hand in the normal meteoric

calcium carbonate water entering the basin and saturating the Upper San Pedro throughout the entire central basin area. Here this is a quality inherited from normal meteoric sources. What interests us particularly is the evidence as to the place and process of the base-exchange, as well as other less obvious modifications.

*Evidence as to Changes Accompanying Migration.* The chemical contrasts between the average normal and modified types of the artesian strain are summarized in Tables 8, 9 and Table 10 (col. 1). They include: (1) *inversion of the alk./alk.ea.* ratio, Na replacing Ca and Mg; (2) slight decrease in $SO_4$ and increase in $H_2S$, suggesting *sulphate reduction;* (3) rK remains more or less constant, so that the ratio rNa/rK changes in parallel with the base-exchange; (4) the ratio rMg/rCa is variable and erratic.

To disclose where and how these changes take place it is necessary to make a closer study of variations within the arbitrary chemical limits of the classification scheme. If any of these are systematic progressive changes accompanying slow oceanward migration in the water well horizons they should be apparent from well-to-well comparisons, even within the basin area where only "normal" waters are encountered in these strata. For this purpose wells of equal spacing and comparable depths were chosen along six "profiles": three across the artesian basin from northeast to southwest, two paralleling the axis, and one southerly down the Santa Ana cone. All of these wells produce water of "normal" types. The evidence thus brought out may be summarized as follows:

(1) No evidence of progressive base-exchange appears within these shallow "normal" *artesian* waters, the inversion of the base ratio being encountered abruptly as the "modified" belt is reached; (2) the carbonate-sulphate ratio undergoes no significant lateral increase until the coastal uplift is reached, where it rises sharply *within* the belt of modified water. In the central basin area this ratio increases with depth only. Near and on the uplifts it increases notably with depth and laterally in an up-structure direction; (3) the ratio rNa/rK closely follows the changes in alk./alk.ea. ratio, rK remaining fairly constant, the alkali of importance

in the base-exchange being Na; (4) the ratio rMg/rCa declines irregularly toward the south and southwest, so it may change in step with distance of migration but is clearly unrelated to the other modifications discussed; (5) total solids tend to decrease slightly down the axis of the syncline, in no way paralleling the other variations.

Thus the restricted occurrence of the modified water in the water wells is not merely due to the arbitrary limits of the classification scheme. Down to depths usually reached by the water wells—around 1000 feet—no evidence of progressive base-exchange is seen. If such a change does occur in the central basin area we must look for it in the waters of the lower and more strongly folded San Pedro strata here below the depths of the water wells, strata which reach the zone of well penetration only in the vicinity of the uplifts.

*Effect of Varying Stratigraphic Penetration.* The vagaries of water well practice make separate sampling of San Pedro aquifers difficult. We know, however, that all but the connate types are found in the San Pedro. Horizons below the Upper San Pedro are believed not to contribute materially to wells producing the *normal* types (1a and 2a), but highly modified water occurs in wells not reaching Lower San Pedro. We can obtain an idea of the effect of varying stratigraphic penetration only indirectly.

*Progressive changes up-structure* do appear in the water wells of the coastal modified belt, even within the narrow chemical limits of the type, where successively lower horizons come into the zone of well penetration. Table 3 shows analyses grouped according to structural position, from wells of roughly similar depths. Though the contrasts are not of the magnitude which distinguish the average normal and modified types, the up-structure group shows a higher average alk./alk.ea. ratio than those of low structural position, with a definite upturn in carbonates (4.5 per cent) which exactly balances decrease in $rSO_4$, and increase in total solids.

Well-to-well comparisons along three "profiles" extending from the normal artesian area to the crest of the coastal uplift at Hunt-

ington Beach, Bolsa Chica and Seal Beach, respectively, are shown in Table 3. The length of each "profile" is two miles. In each the increase in the alk./alk.ea. ratio, the change in carb./$SO_4$ ratio, and the points where marked changes occur are clear. Abrupt increase in rNa and decrease in rCa occurs on the flank of the coastal uplift (two miles basinward, where the wells penetrate only Upper San Pedro strata) with further increase in the alk./alk.ea. ratio up-structure being more gradual. Sharp increase in carb./$SO_4$ ratio is seen only at the structurally highest locations, near the crests of the oil field "structures."

*Variations with increasing depth* at a given structural position are shown by comparing No. 141, a water well far down the basinward flank (Table 3) with deeper samples from a wildcat well nearby—No. 164 and 164A (Table 4). The depths of these samples range between 500 and 2900 + feet. The two shallower samples come from Upper San Pedro only, the deep sample is probably a mixture of waters from both Upper and Lower San Pedro. These give a chemical sequence with increasing depth like that of the profiles, the deepest (164A) clearly belonging chemically with the structurally high group of shallow wells. rMg/rCa definitely increases with depth. The deep sample here has even higher values than the up-structure shallow wells in rNa, rNa/rK, $H_2S$. The increase of carb./$SO_4$ ratio is as prominent here in depth as on the crests of the domes over oil pools.

The variation trends noted within the modified belt are shown graphically in Table 10. Those so far discussed (cols. 1–4) reflect base-exchange and sulphate reduction in increasing degree as deeper horizons of the San Pedro are reached at a basinward flank position on the coastal uplift, and like trends as the crest of the coastal uplift is approached. Finally, we may compare the degree of these changes represented by waters of the extreme stage of modification saturating the Upper San Pedro on and near the coastal uplift with waters from lowermost San Pedro and Upper Fernando (Tables 3–4; 10, col. 5–6). Ten wells (Bouton facies) produce almost wholly from these lowermost zones. The comparisons indicate that waters from these lowest horizons show

little increase in base-exchange, but definite increase in sulphate reduction. All horizons here produce waters of the highest degree of base-exchange. The lowest horizons show changes chiefly due to increase in carb./$SO_4$ ratio, plus effects of contamination with unflushed sea water. The deepest (Bouton facies) shows, in contrast with Upper San Pedro water here, more than double the rCl and notable increase in rMg. Wells of lowest carbonate show highest sulphate. Those with no r$SO_4$ have maximum carbonate and $H_2S$, with no free $CO_2$.

It seems clear that within the modified belt, base-exchange effects increase in degree in the up-structure direction and that as the crest of the coastal uplift is approached the maximum degree is found even in the shallow Upper San Pedro beds. A combination of structural and stratigraphic effects is indicated, with the modified water normally present in the lower horizons under considerable head working stratigraphically higher as the structural barrier along the coast is approached, until near the crest it occurs in all the artesian horizons.

*Wide Extent of Modified Waters at Depth.* The abrupt increase in alk./alk.ea. ratio represented by the appearance of the modified belt in the water wells probably occurs where lower aquifers, not normally reached in the central basin area but in which the modified water is more widespread, first reach the zone of well penetration. That the modified type does have wider extent in depth is shown by its occurrence in certain wells remote from the coastal uplift (Table 4). The Llewellyn sample at Los Alamitos, far out in the area of normal artesian water of the shallow wells; sample 327 from a water well in the southeastern district east of Fairview; and 398 from the northern rim of the basin near Montebello, are such more distant occurrences. The Llewellyn test at depth 3,288 feet had penetrated Lower San Pedro. The Fairview well at 500 feet and the Montebello well at 470 feet produce in part or entirely from Lower San Pedro. The Llewellyn location is well out in the major syncline. The Fairview location is down the basinward plunge of the San Joaquin Hills uplift. The Montebello well is on the north rim of the

artesian basin. The similarities between these samples and those of the coastal belt show that this modified water is really not restricted to the coastal uplift except in the shallower horizons.

Finally the occurrence of modified non-artesian water (type 2b), and of "mixed and modified" waters on the eastern and southern rim of the basin (Fig. 1) shows that here Lower San Pedro and older strata likewise carry highly modified water, though perhaps of somewhat different history. Southeast of Huntington Beach the coastal modified water extends into the edge of the Fairview area of modified water appearing in three shallow wells (325, 327, 328) beyond which it loses its identity. Nearby deeper wells (330, 332, 333) produce modified water of type 2b, while at updip or deeper locations here five wells (294, 303, 313, 323, 326) penetrating lowest San Pedro and perhaps lower horizons produce the "mixed and modified" waters. A very similar area is found along the Santa Fe Springs-Coyote uplift (Fig. 1). Here modified non-artesian water (type 2b) occurs in eight wells scattered over the south flank and westward plunge of this belt up to the edge of the Santa Fe Springs oil field. Along the crest of the uplift east of the West Coyote field seven wells 500 feet to 800 feet deep produce the "mixed and modified" waters. These wells certainly reach lowest San Pedro and probably Upper Fernando.

The average of the twelve samples of "mixed and modified" water found in these two areas is shown in Table 8. This is a highly modified alkaline chloride water, with concentration double that of the non-artesian meteoric strain and much higher Cl. The alk./alk.ea. ratio averages nearly the same as that of the upper oil zone water (type 4a) which represents the highest degree of base-exchange found anywhere in the basin. In other respects this water seems to be chemically intermediate between types 2b and 4a. The occurrences at Fairview would appear to indicate that the water is not merely the result of contamination with oil field waters. Seven other samples similar in reaction characteristics but ranging in concentration from two to three times that of the average of the twelve above mentioned were found during the course of the study. Three were wildcat well samples from the

Puente Hills, two from oil wells in the old Los Angeles City field, one from an old water well at Bimini Baths and one from a wildcat well near Bellflower at depth 4,421 feet. All seven are clearly from pre-Pleistocene strata.

The evidence seems clearly to indicate a widespread occurrence of modified waters in depth.

*Resumé.* In the preceding discussion an attempt has been made to develop the following major points bearing upon the origin and nature of the groundwater modification here:

(1) Five unrelated causes of chemical variation are recognized:

(*a*) Modification of normal meteoric water by base-exchange; extreme results of this process are seen in the composition of the water found generally in the lower part of the San Pedro Pleistocene, and in the Upper Pleistocene in a narrow belt along the coastal uplift.

(*b*) Sulphate reduction with corresponding increase in carbonate and $H_2S$, increasing in degree in general with depth, becoming prominent only in the lowest horizons or at structurally high locations; a relatively minor factor in modification here due to the small quantities of $SO_4$ involved.

(*c*) Appearance in Lower Pleistocene horizons of higher Cl and Mg than normal for the artesian waters, changes indicating slight contamination of modified meteoric water with connate sea water.

(*d*) Effect of nearby outcrops in shallow marginal groundwaters in certain areas of restricted circulation where Mg, $SO_4$ and Cl are higher than normal.

(*e*) Mixture of modified meteoric and connate waters in the pre-Pleistocene oil measures.

(2) The process of base-exchange does not now operate as a systematic progressive modification accompanying the slow oceanward migration of the artesian groundwaters of the Pleistocene. On the contrary its effects appear in the Upper Pleistocene abruptly along the coastal uplift where the waters are under considerable head, and in the lower and persistently marine facies of the Pleistocene wherever wells reach these horizons. Across the artesian area the Upper Pleistocene beds are saturated with un-

modified meteoric water of obvious sources showing no progressive changes in composition until this coastal belt is reached.

(3) There is likewise no evidence of systematic oceanward increase in degree of base-exchange in the deeper horizons. On the contrary highly modified non-artesian waters are found in these beds around the landward margins of the basin. In fact the highest degree of such modification is found in the waters of the Lower Pleistocene and Pliocene horizons in the vicinity of the oil fields around the eastern rim of the basin.

## BASE-EXCHANGE.

Renick (7) has described an interesting case in Montana where waters from shallow wells, relatively high in Ca and Mg, after percolating through certain beds were found to contain little of these but had become relatively high in Na, with no noteworthy changes in the total quantity of dissolved material. He believed that a process of natural softening of the waters here operated due to the content of base-exchange silicates. After reviewing early ideas of base-exchange in groundwaters he pointed out that among natural materials which will thus soften water are greensand or glauconite, bentonite, clay, and that the process is probably aided at least by kaolin, feldspar and mica.

Gale and Scofield, (8) reviewing the ideas of E. McKenzie Taylor, again emphasized the point that the clay and silt fractions of sediments possess the same property of base-exchange as do the "zeolitic minerals," and that silt deposited in ocean water would yield its replaceable Ca and Mg and become saturated with Na in the same manner that a water softener yields its Ca and Mg when "revivified"; and that if after emergence from the ocean it is leached by fresh waters containing Ca and Mg, even in low concentrations, the combined Na may be gradually replaced by the alkaline earths.

Kelley and others, after extensive investigation, have advanced experimental evidence confirming the importance of the role played by the clay minerals, and have given us a clearer picture of the present day views of the process. Thus (9, p. 454)

. . . when a sample of clay is treated with a solution of sodium chloride, if any base exchange takes place however slight, some of the sodium will leave the free solution and become attached to the clay particles, and at the same time a chemical equivalent of some ion held by the clay will leave the solid phase and become a part of the free solution. Although the ion thus absorbed is replaceable by other ions of salt solutions, it does not move out into the liquid freely, except when replaced by some other ion. In a word, the exchangeable ion must be regarded as a part of the solid.

Emphasis is placed on the fact that the replacing power of different cations differs, and that these differences are so great as to be of significance in sediments. Thus Kelley and Liebig (10) state that

The replacing power, or what is sometimes called the energy of replacement of the different metallic cations, differs widely. It is well established that calcium possesses high replacing power; magnesium stands next, followed by potassium and then by sodium. This means that sodium clay is relatively easily converted into calcium clay.

As to the reverse action Kelley (9, p. 455) states:

If a calcium-saturated sediment . . . is leached for a long time with a dilute solution of sodium chloride, only a limited amount of the calcium of the sediment will be replaced by the sodium. . . . A fairly concentrated solution of sodium chloride is required to produce complete replacement of the absorbed calcium from a sediment, but only partial replacement . . . may alter the permeability of the sediment significantly.

On the other hand, if a sodium-saturated sediment is subjected to prolonged leaching with a dilute solution of a calcium salt, such as calcium bicarbonate, practically all the replaceable sodium will ultimately be displaced by calcium and be removed from the sediment, provided the spent solution can drain away from the sediment effectively. . . .

The replacing power of magnesium is also substantially greater than that of sodium. Consequently, sediments, which have been subjected to the action of solutions containing both sodium and magnesium salts, may have acquired as much as, or even more, exchangeable magnesium than exchangeable sodium. A good example of this is found in sediments long subjected to the action of sea water.

However, even though such sediments are strictly speaking not sodium-saturated, when the process is reversed, as it would be

under the influence of the meteoric waters here under discussion, the sodium should be replaced by calcium much more readily than the magnesium, thus giving rise to "modified" waters relatively high in sodium.

The base exchange process is today well established as the important factor in modification of many coastal plain groundwaters. Thus in a recent discussion of sodium carbonate waters on the Atlantic coast Foster (11, p. 846) states:

> The characteristic softening . . . with depth in the water-bearing sands indicates that the sands contain base exchange minerals that are capable of replacing, with sodium, the calcium and magnesium in the waters moving through them. Descriptions . . . frequently note that certain formations are "glauconitic." In other formations . . . in which the waters undergo softening, the base-exchange may be due to certain hydrous alumino-silicates which make up part of the clastic materials of the sediments. As many of the water-bearing sands . . . were deposited in the sea or have been submerged since deposition, any base-exchange minerals contained in them . . . have consequently been subjected once, if not several times, to the action of sea water.

As mentioned in earlier paragraphs the Los Angeles basin Pleistocene is an assemblage of arkosic sands, silts and clays, chiefly of marine origin, having in part at least been repeatedly inundated by the sea. The underlying Pliocene beds are silty and arkosic, and likewise chiefly marine. The basin sediments should thus contain general and widespread agents for base-exchange reactions. Originally these sediments were saturated with sea water, and these agents of exchange had ample opportunity to become charged with sodium and magnesium. In due course the sea water was largely displaced by meteoric waters relatively high in calcium, similar to those entering the basin today. The exchange process was presumably now reversed, since these minerals were no longer in equilibrium with this new chemical environment, the sodium now largely replacing the alkaline earths in the groundwater until equilibrium was again established.

This seems adequate to explain the occurrence of the modified waters found generally in the Lower San Pedro beds, but it does

not explain the restricted occurrence of the modified water along the coastal uplift in the Upper San Pedro. These beds are now charged with normal calcium carbonate water throughout the central basin area, down the axis of the broad regional syncline, the "zone of freest underground circulation" (p. 480), where these unaltered waters actually seek an outlet to the sea at the structurally lowest points along the coastal uplift between Huntington Beach and Newport.

It seems likely that these unaltered shallow meteoric waters have here flushed out an earlier content of modified water, and that the base-exchange minerals already charged with the alkaline earths now no longer serve as agents of modification. In the restricted belt along the basinward flank of the coastal uplift the more strongly folded Lower San Pedro sands carrying the modified water reach the zone of deeper well penetration. Moreover these waters are under considerable artesian head, and when they meet the zone of strong faults along and near the crest of the coastal uplift egress into the overlying Upper San Pedro should be facilitated. Thus these shallow horizons locally become charged with the modified water from below, resulting in the restricted belt of "purest" alkaline water, held up against the structural ridge by the artesian head of the unaltered Upper San Pedro water of the basin area.

The field work involved in this investigation was conducted some twelve years ago. Pressure of other assignments has allowed only intermittent attention to study of the data collected. It is felt that the analytical data listed in the tables, together with the classification and distribution of the groundwater types, represent facts worthy of future consideration in further study of Los Angeles basin groundwaters. The explanation above offered to account for the peculiar distribution of the modified waters of the San Pedro is recognized by the author as a working hypothesis, the validity of which should be tested by future investigators better located and equipped to complete the study.

HOUSTON, TEXAS,
*March 15, 1943.*

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# THE MECHANISM AND ENVIRONMENT OF GOLD DEPOSITION IN VEINS.

WILLIAM H. WHITE.

ABSTRACT.

A study of ores from twenty-seven districts, representing the main types of gold deposits in Canada and the United States, shows that they have a number of characteristic features, some of which are common to nearly all deposits. The process of cataclasis, one of minute fracturing and almost contemporaneous recrystallization of quartz in gold veins, is believed to have been a very important factor in permitting the residual solutions carrying the gold in the veins to permeate the quartz and distribute the gold. Vacuoles are very common in vein quartz and they also play a part. There are some evidences of the temperature at which gold was deposited and it is concluded that in all cases it was relatively low.

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## INTRODUCTION.

THIS paper presents briefly the results of an inquiry into the mechanism and environment of vein-gold deposition. Since no conclusions of consistent validity can emerge from an investigation of the occurrence of gold in any one deposit, twenty-seven vein and lode gold deposits, which varied widely in form, mineralogy, and genetic classification, were studied in both field and laboratory.

These deposits represent most of the important gold camps on the continent (Fig. 1). The general geological setting and structural relations of each deposit were studied and the important mineral associations, textures, and micro-structures were critically ex-

FIG. 1. Geographical Distribution of the Gold Deposits.

amined in thin and polished sections to obtain some idea of the environment of deposition, and to deduce the probable history of formation of each deposit. Comparison of the deposits thus analyzed disclosed some striking similarities. Certain significant features were found to be persistently characteristic of ores of very different type, and it became evident that the process of formation of each deposit conformed to the same fundamental pattern. This basic uniformity of process permits a generalized treatment of the subject of vein formation and justifies generalized conclusions regarding the deposition of gold.

The deposition of gold may be regarded as a subsidiary phase of the process of vein formation. The long and frequently complicated sequence of events which preceded the deposition of the metal will be sketched in a general way in order to consider this important subsidiary phase in its proper perspective. This can be done without neglecting any essential features because of a certain basic uniformity in the process of ore deposition.

## GENERAL CONSIDERATION OF VEIN FORMATION.

*Environment.* Some of the deposits studied were formed at depths probably in excess of 20,000 feet, others, probably within a few hundred feet of the contemporary surface, whereas the majority fall somewhere between these extremes. The static pressures therefore may be assumed to have ranged from over 1,000 atmospheres to less than 100.

A study of the complex structural relations of many vein systems suggests, however, that static conditions rarely obtained. Great differential forces were at work producing complicated strain patterns. In a complex rock mass, the net result was a strongly, and erratically, anisotropic stress environment in which innumerable stress vectors, continually changing, produced a multiplicity of strain features in a confused, superimposed sequence along the composite structural zone. As a rule, such complicated stress environments are characteristic of vein structures formed at various depths. Among the deposits studied, two important exceptions to this rule, are the veins of the Pamour and Broulan mines in the

eastern part of the Porcupine district, Ontario. These vein structures were developed at great depth, but a peculiar combination of circumstances produced relatively static stress conditions.

Temperature is the other important element in the environment of vein formation. Although it cannot be accurately determined for any one deposit, gradually accumulating evidence suggests an upper limit of about 573° C., the inversion point of quartz, and a lower limit which may not be much above 100° C. There is a tendency to assume that the greater the depth, the higher the temperature of vein formation. The validity of this generalization is open to question. Where local heat sources are involved, as they are in problems of ore genesis, the local temperature at a given point in the earth's crust must depend on a number of factors, such as the proximity of the heat source, the quantity of heat, and the relative rates of supply and dissipation. It is conceivable that a heat vehicle, such as a hydrothermal fluid, could produce as high local temperatures near the surface as at greater depth because of the low conductivity of rocks. However, we would expect the temperature to fall more rapidly near the surface. Temperature change during ore deposition will be considered later, but a generalization might be made. During a protracted period of ore deposition it is to be expected that dissipation of heat would finally exceed its accession, since hydrothermal activity is one of the closing phases of a dying magmatic epoch, and consequently that the temperature would gradually fall.

*The Primary Ore Fluid.* The long and frequently complicated train of events in vein formation was initiated when the "primary ore fluid" escaped from its magmatic source and ascended by way of structural channels into the overlying rocks. With the exception of certain substances such as iron and lime which could have been acquired in transit from rocks through which it passed, this juvenile fluid contained all the elements added to the rocks during ore deposition. In addition, it contained water and other substances which remained fluid and disappeared.

The concentration of the primary ore fluid is less evident than its elemental composition. The popular belief, that it was a dilute

aqueous solution, may not be valid in all cases. It is true that almost any ore will show abundant evidence of the facile mobility of the ore fluid, but low viscosity is not necessarily synonomous with low concentration. Furthermore, the writer has found some evidence in the mineral relations of tourmaline and quartz in ores from Bourlamaque township, Quebec, which suggests that the fluid which deposited silica was of sufficient density to exert an appreciable buoyancy on the earlier tourmaline crystals. Although much more evidence is needed, the writer has concluded that the ore-forming fluid may have been rather highly concentrated. Lindgren [1] seriously considers this possibility, and Garrels,[2] in a recent paper dealing with the lead-zinc deposits of the Mississippi Valley, states his belief that high concentrations may be a common feature of hypogene solutions.

*The Nature of the Process of Vein Formation.* The most characteristic feature of all veins is that their constituent minerals were not formed simultaneously, but in a certain sequence. The same fundamental sequence was found in all the deposits studied. First, carbonates and pyrite were formed within the zones of alteration which border all hydrothermal deposits. During this phase the evidence is that only carbon dioxide and sulphur were provided by the primary ore fluid, the basic oxides and iron being furnished by the destruction of pre-existing minerals. Next, more carbonate and pyrite, and in some ores, arsenopyrite or pyrrhotite, were deposited in the earliest vein fractures. These and other fractures were then reopened, and great quantities of silica precipitated to form the predominant quartz of most veins. In the Porcupine district of Ontario and the Bourlamaque district of Quebec, tourmaline occurs in many veins. This interesting mineral invariably occupies a position in the sequence between pyrite and quartz. An alkalic variety of feldspar is found in many veins. Although this may be regarded as reconstituted rock feldspar, nevertheless it occupies a perfectly definite place in the mineral se-

[1] Lindgren, W.: Mineral Deposits, 4th edit. P. 124.

[2] Garrels, R. M.: The Mississippi Valley type lead-zinc deposits and the problem of mineral zoning. ECON. GEOL., 36: 729–744, 1941.

quence. It was deposited before any quartz and slightly later than the earliest carbonate. Many vein contacts are selvedged with massed prisms of this feldspar, the inward-pointing terminations of which are embedded in quartz.

The great majority of veins, particularly those formed at intermediate or great depth, were not deposited as complete units. In the dynamic stress environment featured by a multitude of small, temporary and shifting strains, the vein structures were built piecemeal during a protracted period of local discontinuous dilations. The final size and shape of the vein structure is therefore the composite result of many small increments of mineral deposited where there were innumerable, small and repeatedly superimposed strains. Evidence of their complex construction may be found in nearly all veins. In simple veins, formed by axial reopening of the same vein fractures, the earliest minerals invariably occupy border positions and the later minerals, medial positions. In more complex veins, many textural and structural features, some of which are frequently rather obscure, disclose their composite nature. Replacement is another mechanism of vein formation, of minor importance in most of the veins studied, but prominent in a few. It involved close sheeting or brecciation of a particular zone gradually developing laterally, and accompanied by ingress of ore-forming fluid and progressive alteration of rock minerals. Rock feldspars were made over to a more alkalic variety, excess lime combined to form carbonate, and any original quartz merged with that of the ore-forming fluid.

At this point the primitive vein structures were practically solid bodies, similar in size and shape to those of today. The important difference was, of course, that as yet they contained no precipitated metallic gold. We may now consider the unique train of events which led finally to the enrichment of certain parts of these primitive mineral bodies, thus forming the ores.

### CATACLASIS.

Although by the time the primitive vein structures were completed, the great deformational forces which shaped the larger

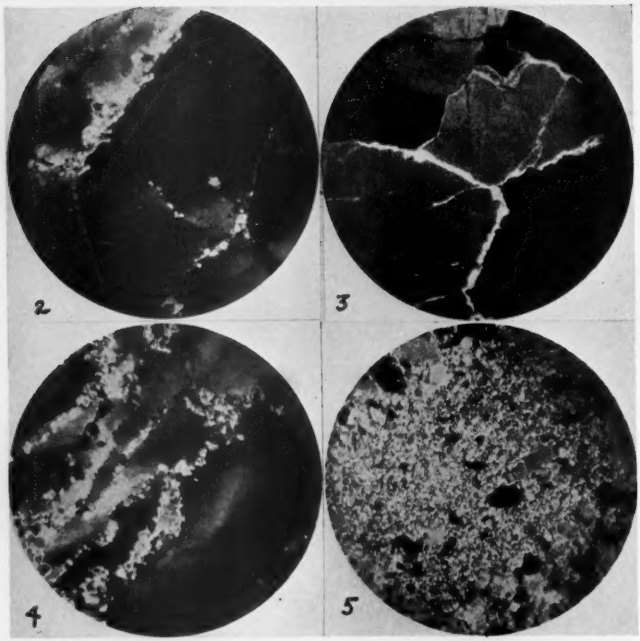


FIG. 2. The incipient stage of cataclastism, showing excessive optical strain and mottled extinction within the large quartz grains, and serrate grain boundaries. Tiny grains of clear "new" quartz are developing in chains along the grain contacts and starting to invade the interior of the original grains.

Buffalo-Ankerite Mine, western Porcupine district, Ontario. ×75, crossed nicols.

FIG. 3. The first hint of cataclasis. The vacuoles, at first random, have become aligned into two intersecting sets of vacuole planes which cross grain boundaries without deflection. The quartz exhibits no optical anomalies.

Eureka Mine, Mother Lode district, California. ×75, crossed nicols.

FIG. 4. A more advanced stage of cataclasis showing the clear fine-grained "new" quartz gradually destroying a large original crystal. There is a suggestion of the banding due to lateral variation in grain size, which will characterize the final state.

structures controlling vein formation had been largely dissipated, a similar, though more restricted, dynamic stress environment still persisted. Consequently, completed sections of the primitive vein structure, while still at somewhat elevated temperature, had to bear local differential stress. Under such conditions, quartz underwent a unique change designated as the "process of cataclasis." Goodspeed [3] recognized the nature of this change, and in his investigation of the ores of the Cornucopia Mine, Oregon, he classified the quartz either as "aclastic" or "cataclastic." The writer has found Goodspeed's classification of quartz applicable to the great majority of quartz veins formed at moderate to great depth. The process of cataclasis is most important in gold deposition.

Cataclasis is a progressive morphological change in vein quartz, and various stages in the development of cataclastic texture may be observed in almost any quartz ore. Original vein quartz usually contains myriads of minute, fluid-filled vacuoles, and the first hint of cataclasis is seen in an apparent rearrangement of these vacuoles. They appear to collect along two principal "vacuole planes." These planes are remarkably regular and are arranged in a definite pattern which extends by en echelon offsets across many grain boundaries. In the remarkable instance of a narrow, regular vein in the Sigma Mine, Bourlamaque district, Quebec, a regular pattern of vacuole planes persists for hundreds of feet. One set of planes is almost parallel and the other highly inclined to the plane of the vein. The arrangement would correspond to the planes of maximum shear in a theoretical strain-ellipsoid properly oriented with respect to either a tangential couple or a compressive force.

[3] Goodspeed, G. E.: Geology of the gold quartz veins of Cornucopia. A. I. M. E., Min. Tech., March, 1939.

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McIntyre Mine, western Porcupine district, Ontario. ×75, crossed nicols.

FIG. 5. The final stage of cataclasis—a completely new texture with small, equidimensional grains of clear "new" quartz. Note the characteristic banding due to lateral variation in grain size.

Eureka Mine, Mother Lode district, California. ×75, crossed nicols.

The next stage is referred to as "incipient cataclastism." Grain boundaries become vague and minutely serrate, and chains and clusters of tiny clear grains of "new" quartz outline the original large turbid crystals. These original crystals lose their optical homogeneity and a striking mottled effect is observed at extinction. Gradually, the interior of the mottled crystals is invaded by chains and clusters of the "new" quartz; vacuole planes are destroyed and the vacuole fluid dispersed; the final result is a completely new texture composed of small, equidimensional grains of clear quartz. Figures 2–5 illustrate the typical development of cataclastic texture.

Cataclastism is not uniform throughout a vein, but is related to various local rolls and crenulations. The zones of most intense cataclastism in regular veins are arranged as parallel, en echelon streaks which lie almost parallel to the plane of the vein. As in the case of vacuole planes, it appears that the arrangement of these zones corresponds to the planes of maximum shear in a properly oriented strain-ellipsoid.

If differential stress is a cause of this unique change in quartz texture, we should find examples of differential strain; and these were abundant in many ores. Early, brittle pyrite crystals were crumbled and the fragments dragged in opposite directions; tourmaline laths, originally embedded in aclastic quartz, were broken into segments, which were slightly separated and offset and then solidly sealed in incipiently cataclastic quartz. Differential stress is therefore one of the prerequisites of cataclasis.

The other prerequisite is that the temperature be above a certain minimum value. In some ores it was found that the sequence of cataclastic strains—for they do occur in sequence and are frequently superimposed—finally gave place to a sequence of purely mechanical strains. The quartz was merely pulverized as with a hammer. After some practice it is easy to differentiate between a finely cataclastic texture and a brecciated texture. The only change of environment which could have occurred during this change in the type of strain was drop in temperature. Therefore, a certain minimum temperature is the other prime requisite of

cataclasis. Although it cannot be defined too closely, it was probably between 200° and 300° C.

During cataclasis, the quartz is in a metastable condition and there is good evidence that some at least becomes transiently

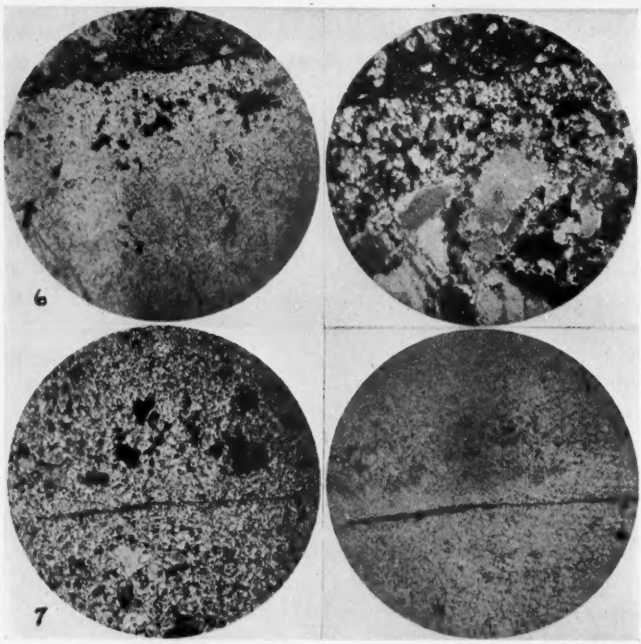


FIG. 6. Twin photomicrographs. Left, plane polarized light and right, crossed nicols. Minute arsenopyrite crystals in cataclastic quartz along a fragment contact. Note the distribution of the arsenopyrite crystals in relation to the intensity of cataclastism.

Delnite Mine, western Porcupine district, Ontario. ×75.

FIG. 7. Twin photomicrographs. Right, plane polarized light; left, crossed nicols. Minute arsenopyrite crystals forming a regular narrow band in quartz which is seen to be cataclastically banded, the arsenopyrite streak being restricted to the axis of the most finely cataclastic band. There is another similar band just above this field.

Eureka Mine, Mother Lode district, California. ×75.

mobile. For example, veinlets of clear quartz, which might be mistaken for separate later injections, are found to merge without break in both directions into zones of intense cataclastism. Again, brittle minerals such as galena, which were deposited later than quartz, may be fractured and cemented by clear quartz which is obviously the same as the adjacent highly cataclastic material. On the other hand, while the quartz exists in this metastable condition it still retains sufficient rigidity to maintain myriads of minute open seams which are the avenues of access of the later mineral-bearing fluid. Cataclasis might be broadly defined, therefore, as a process of micro-brecciation and simultaneous recrystallization.

Another feature of cataclasis is that, although the quartz has recrystallized, this has not resulted in decreased porosity of the vein material as a whole. On the contrary, cataclastic sections are very much more permeable than aclastic. Detailed examination shows the small "new" grains of cataclastic quartz packed together as in a loosely cemented sandstone, leaving myriads of minute inter-granular spaces—not interlocked like those of a quartzite.

## DEVELOPMENT OF THE RESIDUAL ORE FLUID.

Among the variety of substances comprising the primary ore fluid, gold was a very insignificant constituent. However, as deposition proceeded, various non-auriferous constituents, carbon dioxide, sulphur, iron, arsenic, and silica were abstracted in sequence and fixed as vein minerals; consequently, the relative proportion of gold increased tremendously. Consideration of the structural and textural features of the primitive veins, prior to the deposition of gold, seems to supply an answer to the nature of this gold-rich fluid.

The veins of the Pamour and Broulan mines are unique in that no post-quartz strains [4] modified their original character. The vein quartz is still in the original form of coarse-grained subhedral crystals, unfractured and completely aclastic. Gold and associ-

[4] This refers only to post-quartz strains occurring during the period of ore deposition.

ated minerals occur interstitially among the subhedral quartz crystals as thin films along grain boundaries, and as larger plates molded upon crystal surfaces (Fig. 8). These veins attained their present dimensions with complete deposition of quartz; consequently, the fluid which contained the gold was confined to small interstices such as grain boundaries and small crystal-bounded vugs. There was no way for it to get into or out of these solid quartz bodies, and even limited migration along the veins was

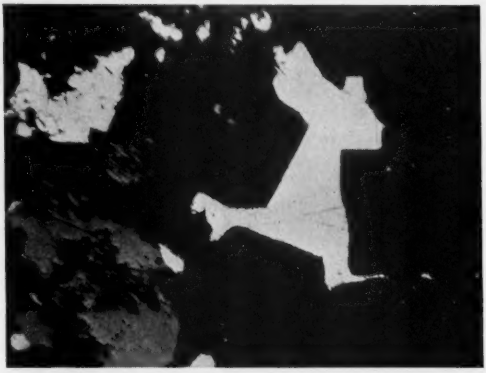

FIG. 8. Gold, galena (partially etched), and sphalerite filling a vug between quartz crystal surfaces. Sphalerite appears to be a little earlier than gold and galena. Fractured and complete crystals of early pyrite are seen to the left. The subhedral quartz crystals have remained undisturbed since their formation.

Broulan Mine, eastern Porcupine district, Ontario. × 50, polished section.

almost prohibited by the scarcity of continuous passages. Similar reasoning applies to the more general type of vein. Among the deposits studied, the most careful examination failed to reveal any evidence of major post-quartz strains which could have been the means of access of large volumes of fluid. Cataclastic sections are typically local phenomena and the strains which caused them were of a local character. This is particularly well illustrated in the Sixteen-to-One Mine, Alleghany district, California, where the

stoped areas of cataclastic ("live") quartz were found to be bounded on all sides by solid, aclastic ("dead") quartz. Consequently it is concluded that the total porosity of the typical primitive vein structure depended upon the intergranular spaces of aclastic sections and the more numerous interstices of cataclastic sections.

It may now be assumed that there is no mechanism [5] whereby a large volume of fluid could be moved through these relatively impermeable primitive vein structures against the tremendous frictional resistance of the myriads of minute, disconnected passages through which it would be obliged to pass. The alternative, that the volume of fluid must have been relatively small and of necessity rather highly concentrated, must therefore be true. This "residual ore fluid" contained relatively large quantities of gold and soda or potash, or both, and varying quantities of other substances, such as iron, arsenic, lead, zinc, copper, sulphur, and silica. In its mode of derivation, and its diverse composition, the residual ore fluid is analagous to the "residual magma" of the petrologists.

This conception of ore genesis is not altogether in harmony with currently popular views. From a theoretical standpoint, the derivation of this relatively concentrated residual ore fluid becomes difficult if the primary ore fluid is assumed to be a very dilute solution. With extraction of the common mineral constituents, the solution would become still more dilute, and derivation of the small concentrated residuum would then necessitate the separation of a large fluid fraction barren of gold and associated minerals. If, on the other hand, the original fluid were somewhat concentrated, a view which has much to commend it, derivation of the concentrated fluid residuum would be more easily understood.

Furthermore, this conception of the subtractive process whereby gold, present in the ore fluid since the beginning of ore deposition, finally becomes concentrated and appears as the solid metal late in the sequence, is inconsistent with the views of those who believe that gold is "introduced" into the hitherto barren veins from some

[5] Except by allowing an excessive length of time, of which there is no evidence.

extraneous source. The writer finds no support for such views in this study of the many ore samples examined. The exceptional occurrence of gold in the Pamour and Broulan mines, which has been mentioned, and the absence in other deposits of any possible channels of access, contradict a theory based on the later introduction of gold-bearing fluid. The distribution of various minerals and the timing of depositional events in gold deposits generally are too perfectly synchronized to be coincidental. Farmin [6] draws an apt illustration from the veins of the Grass Valley district, California. Here, dozens of veins traversing cubic miles of host rock, all have about the same tenor of post-quartz sulphides and gold. For these to have been introduced from an extraneous source would have required a synchronization of strains within specified zones in cubic miles of rock, and a nicety of timing which appear quite beyond the realm of possibility. The conclusion must be, therefore, that gold and other late minerals were present during the entire period of vein formation and, as persistent fluid constituents, became progressively concentrated in the shrinking volume of fluid, to appear as solid minerals only near the end of the entire sequence.

## DEPOSITION OF GOLD.

The tenor of veins is by no means uniform. Many have an almost rhythmic alternation of mineralized and unmineralized sections, and of ore shoots separated by barren stretches. Even within ore shoots the gold and associated sulphides are apt to occur in streaks which tend to have an en echelon arrangement almost parallel to the plane of the vein. Such distribution is by no means accidental. It shows exactly the locus of permeation of the residual ore fluid. In ores such as those of the Pamour and Broulan mines, fluid permeation was widely diffused among many accidental interstices in the undisturbed vein material, and consequently the late sulphides and gold are similarly disseminated. In the more typical vein, the cataclastic sections, which are rela-

[6] Farmin, Rollin: Host-rock inflation by veins and dikes at Grass Valley, California. ECON. GEOL., 36: 168, 1941.

tively more permeable than the intervening aclastic ones, were the loci to which the residual ore fluid diffused from all directions.

Within the cataclastic sections a subsidiary depositional sequence was initiated which was just as definite as that of the earlier stage of vein formation. The typical order of deposition is pyrite, arsenopyrite (if present), sphalerite, galena, and gold, with sericite[7] or carbonate (or both) continually depositing throughout the sequence.

The distribution of each mineral of this subsidiary phase was intimately related to the contemporary strain features. The earlier sulphides were deposited during one or more of the minor periods of cataclasis which were frequently superimposed. The fidelity with which these minerals were restricted to zones, or even lines of cataclasis, is remarkable, and it may be stated as a consistent rule that no mineral of this subsidiary phase of deposition ever occurs in solid, aclastic quartz. Furthermore, these minerals are restricted not only to the cataclastic zones, but to the most intensely cataclastic parts of such zones. This intimate relation is illustrated by the twin photomicrographs in Figures 6 and 7. The inference is that the most finely cataclastic quartz was also the most permeable to the residual ore fluid.

During this period of deposition, conditions had been gradually moderating, and in an environment of waning cataclasis swarms of tiny cracks appeared, forming parallel branching patterns through the cataclastic quartz. These were the 'trunk lines' of movement of the remaining residual fluid, now heavily charged with gold, usually a little galena, and, in one deposit, stibnite. From these trunk lines, the fluid diffused laterally into the minute interstices of cataclastic quartz or into tiny fractures in earlier brittle minerals, such as pyrite or feldspar, where the gold and the last traces of sulphide were deposited. Sericite, less commonly carbonate, is the invariable associate of gold, and it apparently continued to deposit after all the gold had crystallized. This is the last constituent of the residual ore fluid of which there is a

[7] White mica deposited during this period is referred to as "sericite" although it is suspected that the mineral contains an appreciable proportion of soda.

record. If any fluid remained it has disappeared in the course of time, leaving no clues to its identity.

### THE MECHANISM AND TEMPERATURE OF GOLD DEPOSITION.

The larger mechanism by which gold became concentrated in the residual ore fluid has been discussed. The single and sufficient mechanism whereby this residual ore fluid was distributed appears to have been diffusion. The delicate control of differential permeability over the distribution of the gold-bearing fluid is well illustrated by the twin photomicrographs of Figures 11–13. In Figure 11, gold was deposited from a fluid which followed a serrate line of more intense cataclasis, and in Figure 13 the gold-bearing fluid, following one of the main trunk-line seams, diffused laterally into a zone of minutely cataclastic quartz where its gold precipitated as minute crystals. The faithful restriction of gold and contemporary stibnite crystals to cataclastic lines is illustrated by Figure 12.

Gold, the last metallic mineral to be deposited, is intimately related to minor strain features which post-dated the general period of cataclasis. For example, in the ores of the Cornucopia Mine gold occurs in very local fractures or zones of mechanical brecciation which traverse aclastic and cataclastic quartz alike (Fig. 9); a similar situation is found in the conglomerate ores of the Dome Mine. Moreover, in the peculiar ankerite veins of the latter mine, gold occurs in minutely serrate cracks which wander through the coarsely crystalline carbonate and which evidently originated by slight tensional adjustments within the vein structures (Fig. 10). Similar relations were observed in other ores. It appears reasonably certain, therefore, that a very low-stress or even non-stress environment is typical of the final stage in gold deposition.

The fact that gold was deposited where strains occurred subsequent to the period of cataclasis implies that the temperature of deposition was below that requisite for cataclasis. However, there is other evidence of a low temperature environment. Among the intimate mineral associates of gold a few provide some evidence of the temperature of gold deposition. Of these, realgar

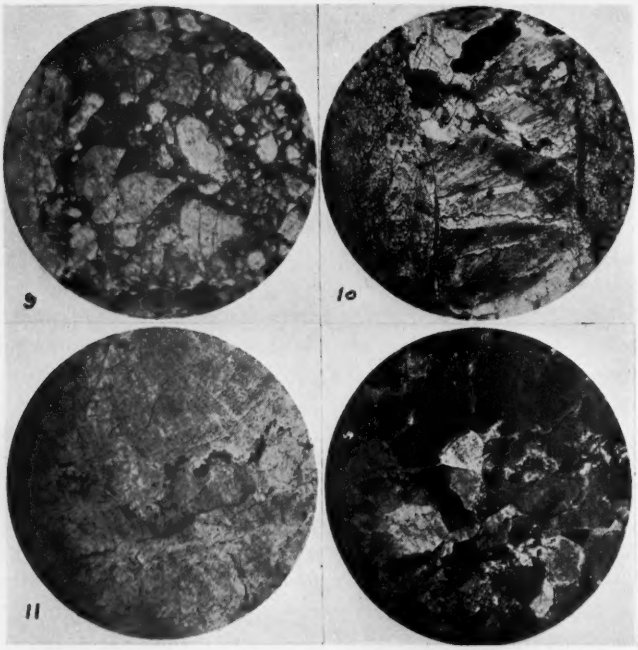


FIG. 9. A zone of mechanical brecciation which affected both aclastic and cataclastic quartz. The angular fragments of quartz are set in a matrix of sericite and carbonate. The typical occurrence of gold is as fine particles distributed along such zones. The black material is fractured early pyrite.

Cornucopia Mine, Oregon. × 35, plane polarized light.

FIG. 10. A carbonate veinlet showing the minutely jagged cracks which tend to follow crystal boundaries and cleavages. Gold occurs in minute particles here and there along these cracks. Black area is earlier pyrite.

Dome Mine, Porcupine district, Ontario. × 75, plane polarized light.

FIG. 11. Twin photomicrographs. Left, plane polarized light; right, crossed nicols. A styliolite-like sericite seam containing gold and several arsenopyrite prisms. Note that the seam faithfully follows cataclastic lines and grain contacts through quartz which exhibits incipient cataclastism. Although arsenopyrite and gold are both post-quartz minerals and

and stibnite are the most diagnostic. In the relatively shallow-seated ores of the Getchel Mine, Nevada, realgar is found intimately related to gold in the latest carbonate veinlets. Identical relations between gold and realgar are present in the deep-seated ores of the Homestake Mine, South Dakota. Since realgar is stable only at low temperatures, in the vicinity of 200° C., it is evident that the gold associated with it must have been deposited at the same moderate temperature. Stibnite, a typically low temperature mineral, is common to the epithermal ores of Cripple Creek, Colorado, and the relatively deep-seated ores of the Negus Mine, Northwest Territories where it is intimately related to gold. Warren [8] has recently discovered that native gold in many deposits contains detectable quantities of mercury. These data suggest that gold is deposited at a temperature which may not be above 200° C. and which may well be considerably below that temperature. Furthermore, it should be noted that this is the temperature of gold deposition in any deposit, whether it is classed as hypothermal, mesothermal, or epithermal.

The fact that the residual ore fluid was able to diffuse into almost submicroscopic interstices is ample proof of its extremely mobile nature. From the intimate mineral relations of gold it may be concluded that the residual ore fluid was a true solution, and that gold was not, as is supposed by some geologists, transported as colloidal particles. If such were the case, there should be a separation of constituents along the walls of the main trunk-line seams, the larger gold particles remaining at the walls and the fluid constituents diffusing into the adjacent minute interstices. This is not the case. Scattered through the finely cataclastic quartz which usually borders the trunk-line seams, we frequently find minute crystals of gold, galena, and in one deposit, stibnite, all

[8] Warren, H. V.: Personal communication, March, 1942.

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appear to be closely associated, detailed examination showed that the arsenopyrite was deposited much earlier and that the fluid which precipitated gold merely followed the same permeable line.

Bralorne Mine, Bridge River district, British Columbia. ×75.

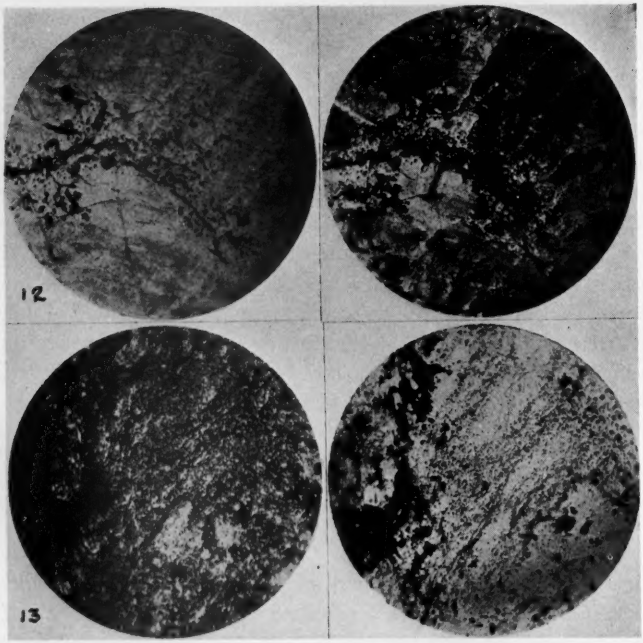



FIG. 12. Twin photomicrographs. Left, plane polarized light; right, crossed nicols. This is another illustration of the fidelity with which the residual ore fluid followed cataclastic lines which were lines of maximum permeability. This is the frayed termination of one of the characteristic "trunk line" seams. The black particles are gold, galena and stibnite. Many of the smaller ones are complete crystals.

Negus Mine, Northwest Territories. ×75.

FIG. 13. Twin photomicrographs. Right, plane polarized light; left, crossed nicols. A section through a gold-plated "trunk line" seam, showing the manner in which the gold-bearing fluid diffused laterally to deposit its gold as minute crystals in the interstices of a contact band of very finely cataclastic quartz. Just beyond the field the quartz rapidly becomes aclastic and there no gold occurs. Minute crystals of carbonate are scattered through the quartz, apparently being contemporary with the gold.

Negus Mine, Northwest Territories. ×75.

intimately and mutually associated. This implies that all constituents were transported in the same state; probably all were present as dissolved constituents of a residual ore solution.

## CONCLUSIONS.

The presence and distribution of gold within veins is not a matter of chance, but is the logical result of a unique train of events occurring under certain favorable conditions. Gold, present in very minor proportion in the primitive hydrothermal fluid, by a rational process of subtractive crystallization of non-auriferous minerals, became progressively concentrated and finally comprised one of the principal metallic constituents of a very mobile, residual solution unlike the parent fluid. By virtue of its ability to diffuse readily, this residual fluid collected in any sections of the vein structure offering enhanced permeability. Cataclastic sections, having very superior permeability, were the favored areas to which the residual ore fluid diffused. It is a remarkable fact that where gold occurs in well-defined ore shoots, the quartz of such shoots is invariably cataclastic, and the limits of the ore mark the limits of cataclastic modification. A subsidiary sequence of mineral deposition occurred within these cataclastic sections. Gold was the last metallic mineral to crystallize, its closest sulphide associate being galena, and occasionally stibnite, realgar, and cinnabar.

Gold was deposited under uniform conditions of low and waning stress at a temperature possibly less than 200° C. Whatever the initial temperature of vein formation may have been, whatever the genetic classification of the deposit in which it occurs, gold remained a constituent of the residual ore fluid, and did not appear as the solid metal until a consistently low temperature had been attained.

## ACKNOWLEDGMENTS.

The writer is deeply indebted to the officials at the many mines investigated for permitting him to visit their properties and obtain specimens for study, and to those who kindly sent him material

for examination. The task of collecting and cataloguing material and arranging data was facilitated by Elizabeth U. White, to whom the writer expresses his thanks. He wishes also to express his thanks to Professors E. S. Moore and G. B. Langford for suggestions, and criticism of this paper.

DEPARTMENT OF GEOLOGY,
UNIVERSITY OF TORONTO,
TORONTO, ONTARIO,
*April 21, 1943.*

# DISCUSSION AND COMMUNICATIONS

## *LABORATORY EVIDENCE CONCERNING THE INTERPRETATION OF ASYMMETRICAL CRYSTALS.*

*Dear Sir:*

The purpose of this communication is to call attention to the published results of laboratory experiments pertinent to recent discussions which have appeared in this journal concerning the direction of flow of mineralizing solutions.[1]

Spezia[2] produced additional growth on a quartz crystal (Japanese twin) whose long direction was placed horizontally, with the source of supply of the silica above the crystal. In Figure 3 the stippled part represents the crystal before the experiment. Two of the terminations of the twin were broken, but the third, shown on the left in Figure 3, was terminated by rhombohedral faces. The apex of this termination is nearer the lower side of the crystal than the upper.

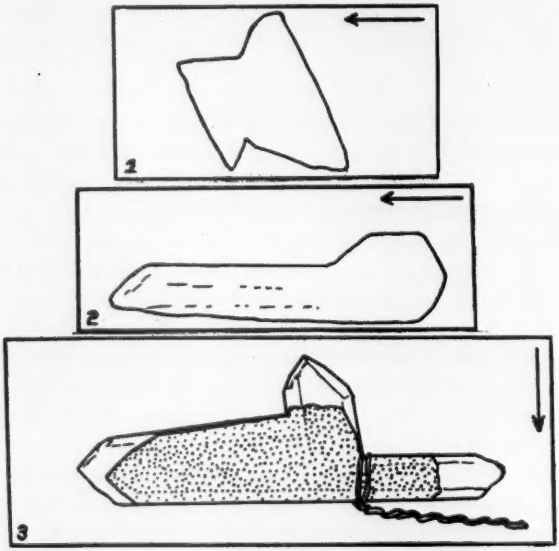
The additional growth shown in Figure 3 was produced by silica-bearing solutions moving in the direction indicated by the arrow. Both the new terminations of the horizontal part of the crystal have their apices nearer the upper side of the crystal, the "stoss" side, the side first reached by the solutions, and their greater growth on this side is clearly indicated at the left end of the crystal.

[1] Newhouse, W. H.: Direction of flow of mineralizing solutions. ECON. GEOL., 36: 612–629, 1941.

Bandy, M. C.: Direction of flow of mineralizing solutions. ECON. GEOL., 37: 330–333, 1942.

[2] Spezia, Giorgio: Sull'accrescimento del quarzo. Atti della Reale Accademia delle Scienze di Torino, 44: 95–107, 1908. A description of the conditions of this experiment, with photographs of the enlarged crystals, may be found in Recorded experiments in the production of quartz, G. S. A. Bull. 54, Suppl. 1, 1943, by Paul F. Kerr and Elizabeth Armstrong.

The vertical part of the crystal has grown a termination whose asymmetry exceeds that of the other two. This might be interpreted either as indicating cross currents in the descending solutions or as indicating that factors other than the direction of flow of the solutions influenced the habit of growth of the crystal.




FIGS. 1–3.

Dreaper [8] produced lead chloride crystals in a capillary tube which contained a 3 per cent lead acetate solution. The open end of this tube was placed in a horizontal position in a 5 per cent solution of hydrochloric acid. The lead chloride crystals formed slowly in the capillary tube, growing larger on the side or end first reached by the solutions. They are shown in Figures 1 and 2, in which the arrows indicate the direction of solution-movement.

[8] Dreaper, W. P.: Niederschlags- und Schichtenbildung in Abwesenheit von Gelen. Kolloid-Zeitschrift, 14: 163–166, 1914. Plate facing page 170.

Dreaper suggests (p. 164) that such asymmetrical growth with respect to solution-movement "can perhaps be used to explain similar phenomena which may possibly have occurred in nature in the past."

ELIZABETH ARMSTRONG.

BELL TELEPHONE LABORATORIES,
NEW YORK CITY.

# REVIEWS *

**Minerals in World Affairs.** By T. S. Lovering. Pp. viii + 394; Tables 50. Prentice-Hall, Inc., New York, 1943. Price, $4.00.

**World Minerals and World Peace.** By C. K. Leith, J. W. Furness, and Cleona Lewis. Pp. 253; Pls. 15; Tables 41. Brookings Institution, Washington, 1943. Price, $2.50.

One of the greatest guarantees for a perpetuation of peace would be mineral self-sufficiency of industrial nations. On the other hand, the unequal distribution of important minerals, resulting in "have" and "have not" nations, has been one of the dominant causes of aggression. Equitable distribution of all the minerals required by industrial nations must be realized as a problem that should indeed be included in the post-war planning.

Maintenance of supplies of minerals necessary to industry but not obtainable in adequate quantities domestically—the strategic minerals—presented a national problem in World War I. Since that war the United States has paid greater attention to the problem than at any other time in history. It is now evident that in preparation for the present war the axis nations were even more concerned over their lists of strategic minerals, for they built huge stock piles and fostered development of mines in the neighboring countries that were soon to be taken over or dominated. The fact that the United Nations control the bulk of world mineral resources may well be as powerful an influence in the cessation of hostilities as it was in the creation of World War II. Certainly it has determined campaigns and was a central factor in the concept of geopolitics.

T. S. Lovering and the authors of *World Minerals and World Peace* have presented the problems created by the location of mineral supplies and have shown that the interdependence of nations for these supplies will not be lessened. In both books abundant data inform the reader of world mineral distribution and of production trends. A comparison of the essential minerals available to the warring groups is a dominant theme in both.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

*Minerals in World Affairs* is written by an economic geologist, primarily interested in presenting a discussion of world minerals. He does not dwell upon the implications or suggest possible solutions; this may be considered a serious deficiency. The author has ably discussed the peculiarities of mineral economics resulting from localization of occurrence, exhaustibility, discovery hazards, and scrap supply. Methods of alleviating the problem resulting from scarcity of minerals are presented. The place of minerals in history is included in two chapters: Before the Industrial Era, and During the Industrial Era. A chapter on geology sets the stage for parts II, III, and IV in which each of the important minerals is discussed in regard to its properties, uses, substitutes, technology, distribution, production, commercial control, and national policies. Although this book appears weaker in the economic and political phases than *World Minerals and World Peace,* its splendid presentation of the geologic aspect of the pertinent minerals makes it a distinctive and useful volume.

*World Minerals and World Peace* is written by a geologist, a mineral statistician, and an economist. C. K. Leith has been concerned with the world mineral problem since World War I when he was named mineral advisor to the War Industries Board. He has written several books and papers on the subject since that time and in the present war he has been consultant on minerals for the War Production Board. J. W. Furness is a former Chief of the Economics and Statistics Branch of the Bureau of Mines. Cleona Lewis has written several volumes in the field of international economic relations. The book sets forth the world mineral picture as it exists today. The development of mineral output, the introduction of "new" minerals into industry, and the geography of mineral production are sketched. Emphasis is placed on the influence of minerals on world economics and politics. Economics of mineral industries and geology is only briefly treated. Part III, The Future, is a discussion of the phase referred to in the second half of the title. It is here shown that the axis nations—"have not" nations—were neither denied access to world minerals nor discriminated against prior to the war. The implications set forth in the Atlantic Charter are discussed and the conclusion drawn that world peace will result from strict prevention of war preparation and that control of necessary minerals is essential to such a policy. This problem is too vast to be adequately covered in one chapter, and the reader will feel that the authors could have done more by way of discussing world peace.

The timeliness of these books and the importance of the subject cannot be questioned. Both are well written and will serve as excellent sources for instructors in economic geology, international relations, and economics.

Both may be readily understood by readers untrained in geology or economics.

RALPH E. DIGMAN.

**Geomorphology. The Evolution of Landscape.** By NORMAN E. A. HINDS. Pp. xi + 894; Figs. 771. Prentice-Hall, Inc., New York, 1943. Price, $5.00.

"This book, in its brief compass, tells how the face of the earth has come to look as it does today." It is "planned for the student and the general reader uninitiated, or nearly so, in earth lore. It is not written to inform those already expert in the subject." With the purpose clearly stated in the preface, the author presents a well-arranged and non-technical discussion of scenic features with an explanation of their origin and development. Over half the page space is devoted to halftone reproductions. Although these pictures are a distinct asset to the book, it does seem wasteful to publish so many views of the same region, and even more extravagant to repeat individual pictures (pp. 446 and 827, 495 and 548, 88 and 380).

Chapter headings are based on natural agents that work to mold the features of the earth's surface. In addition, the origin of the earth, the age of the earth, interpretations of topographic maps, descriptions of natural bridges and submarine canyons have been included. A list of selected references and a list of topographic sheets illustrating the subject matter is appended to each chapter. The text is clearly written although some repetition and a few inconsistencies can be noted.

Of definite value to advanced students and teachers is the 34-page bibliography of technical books and papers which follows the final chapter. Although incomplete, it is sufficiently thorough to aid investigation in any of the various topics.

The non-professional student as well as advanced workers will find useful information, but the multitude of pictures and simplicity of description make the book particularly valuable for the traveller in America —especially in the West.

**Minerals and Rocks.** By RUSSELL D. GEORGE. Pp. xviii + 595; Figs. 150; Pls. 48. Appleton-Century, Inc., New York, 1943. Price, $6.00.

When the subjects of rocks and minerals are combined within one book, a large amount of factual information must be necessarily sacrificed. Dr. George, however, realizing that a concise yet broadly inclusive book dealing with these topics would be of value, set about the task of producing in a single survey the entire field of earth materials. His long experience as professor of geology at the University of Colorado, as well as his position as State Geologist of that state equipped him admirably for the task.

The book is one of the Century Earth Science Series, edited by Professor Kirtley Mather. Two introductory chapters briefly discuss the materials of the earth, properties of minerals and the origins and forms of metalliferous ore deposits. The text is divided into five parts, Metallic Elements and Minerals, Non-Metallic Elements and Minerals, Rock-Making Minerals, Determinative Mineralogy, and The Common Rocks. The appendix, Materials Classified by Uses, is quite thorough and will be valuable. The two-page glossary is too brief to be of aid but the excellent text index offsets this deficiency. The 48 plates picturing characteristics of many rocks and minerals have been well selected and are an aid to the text descriptions.

*Minerals and Rocks* will find limited use as a textbook in mineralogy and petrology courses but may be used to good advantage in the parts of these subjects dealing with economic mineralogy and petrology. Mineral collectors and prospectors will find it valuable as a field handbook since pertinent data and pictures of common earth materials are here contained in a single volume.

## BOOKS RECEIVED.

RALPH E. DIGMAN.

**Micrometrics, The Technology of Fine Particles.** J. M. DALLA VALLE. Pp. xiv + 428; Figs. 100. Pitman Pub. Corp. (24 W. 45th St.), New York, 1943. Price, $8.50.

**Years of This Land.** HERMANN R. MUELDER AND DAVID M. DELO. Pp. 243; Figs. 11; Pls. 11. D. Appleton-Century Co., New York, 1943. Price, $2.50.

**Review of Petroleum Geology in 1942.** F. M. VAN TUYL. Pp. 75. Colorado School of Mines Quarterly. Vol. 38, July 1943, Golden. Price, $1.00. *The head of the Department of Geology of the Colorado School of Mines presents a concise account of the developments during the past year in the field of petroleum geology. The influence of the war on geologists and geophysicists and their contributions are noted. Important events in the fields of geology, geophysics, geochemistry, geobiology, petroleum engineering, and aerial photography are included as are recent figures on production and reserves. The work was compiled through the cooperation of the Research Committee of the A.A.P.G. and presented in part at the 1943 convention of the Association. Similar "Reviews" will be published annually by the Colorado School of Mines.*

**Canadian Mines Handbook, 1943.** Pp. 259. Northern Miner Press, Ltd., Toronto, 1943. Price, $1.00. *A valuable reference volume with considerable statistical information on the mines of Canada. Part I deals with the active companies and considers the executive and managerial personnel of each company and its earnings. History, properties,*

*development, reserves, and production are briefly stated for each. Part II of the book contains a supplementary list including inactive and extinct companies. The last similar book was published early in 1942.*

**Geologic Formations and Economic Development of the Oil and Gas Fields of California.** OLAF P. JENKINS, Dir. Pp. xvi + 773; Figs. 284; Pls. 6; Map 1. California Department of Natural Resources, Bull. 118, San Francisco, 1940–1943. Price, $4.00. *Probably one of the largest and most thorough undertakings of any state geologic survey, this bulletin will stand for many years as the leading authority on the oil and gas resources of California. Prepared under the direction of Olaf P. Jenkins, Chief Geologist of the Geological Branch of the California Division of Mines, the bulletin contains contributions from 126 authors. The work is now available in four preprint parts: Part one, Development of the Industry; Part two, Geology of California and the Occurrence of Oil and Gas; Part three, Descriptions of Individual Oil and Gas Fields; and Part four, Glossaries, Bibliography, and Index, including Outline Geologic Map of California Showing Oil and Gas Fields and Drilled Areas, scale 1:1,000,000. Page size is 8½" × 11". A final cloth-bound volume of all four parts is to be prepared and will sell for $6.00. Individual copies of the outline map are available at $1.00 each.*

**Some Mineral Deposits in the Area Surrounding the Junction of the Snake and Imnaha Rivers in Oregon.** F. W. LIBBEY. Pp. 17; Pls. 5. Dept. of Geol. and Min. Industries, G. M. I. Short Paper, No. 11, Portland, 1943. Price, 15 cents.

**Bibliografia Geologica de Bolivia.** V. OPPENHEIM. Pp. 19. Del Boletin de la Sociedad Geografica de La Paz. Ano LIII, No. 65. La Paz, Bolivia, 1943.

**Gold Coast Geological Survey,** Accra, Gold Coast Colony.

**Report on the Geological Survey Department, 1939–40.** N. R. JUNNER. Pp. 32, 1940.

**The Tarkwa Goldfield.** N. R. JUNNER AND OTHERS. Pp. 75; Pls. 26. Mem. No. 6, 1942.

**U. S. Bureau of Mines.** Washington, 1943.

**Syllabus of Clay Testing, Part 1.** T. A. KLEINFELTER AND OTHERS. Pp. 35; Figs. 12. Bull. 451. Price, 15 cents.

**Carbonizing Properties and Petrographic Composition of Taggart-Bed Coal from Mines 30 and 31, Lynch, Harlan County, Ky., and the Effect of Blending this Coal with Pocahontas No. 3- and No. 4-Bed Coals.** J. D. DAVIS AND OTHERS. Pp. 45; Figs. 25. Tech. Pap. 650. Price, 10 cents.

**Coke-Oven Accidents in the United States, 1941.** W. W. ADAMS AND V. E. WRENN. Pp. 19; Figs. 3. Tech. Pap. 651. Price, 10 cents.

**Explosion Hazards of Combustible Anesthetics.** G. W. JONES, R. E. KENNEDY AND G. J. THOMAS. Pp. 47; Figs. 21. Tech. Pap. 653. Price, 15 cents.

# SOCIETY OF ECONOMIC GEOLOGISTS

## CYRUS FISHER TOLMAN.

### 1873–1942.

Cyrus Fisher Tolman, Professor Emeritus of Economic Geology and beloved "Chief" to hundreds of Stanford alumni and fellow geologists, succumbed to a heart attack in Spokane, October 13, 1942. He died, as he would have wished and as he knew he might, suddenly in the midst of strenuous professional work. He leaves behind a very real vacancy in economic geology and a poignant feeling of personal loss in the hearts of all who knew him well. Few geologists have contributed so much to the development of the natural resources of the West and in such varied fields as mining, petroleum, and groundwater geology.

Born in Chicago on June 2, 1873, he obtained his B.S. degree in 1896 from the University of Chicago. Except for a period of service in the Spanish-American War, he remained at Chicago as graduate student and fellow until 1899. In 1900 he married Miss Hannah Van Steen.

His first professional work was at Butte in 1899, as assistant to H. V. Winchell. Here he first became interested in secondary enrichment in copper ores, to which he later made noteworthy contributions. From 1905 to 1912, he was Professor of Geology and of Mining at the University of Arizona, and he served as Territorial Geologist from 1910 to 1912. In the latter year he joined the faculty at Stanford University, where he was for 26 years Associate Professor and Professor of Economic Geology, retiring in 1938 as Professor Emeritus.

He won renown as a highly successful teacher of both petroleum and mining geology, and developed outstanding courses in field geology under the name of Stanford Geological Survey. He became a leader in scientific study and instruction in groundwater geology; his book "Ground Water," published in 1937, is the first authoritative and comprehensive text book on this subject in English. He was active as a consultant in mining, petroleum, non-metallic, and groundwater geology, and was employed by numerous large corporations, municipalities, and individuals.

After retiring from teaching, he continued as an energetic investigator and consultant in the field, especially since the present war began. During the last years of his life he served his country well as chief geologist for a giant corporation conspicuously important in the war effort.

"Chief" Tolman led a very full and active life. By his work he contributed greatly to the factual data on which geology is based. In his teaching he brought to his students a realization that the science can be at once a fascinating study and an instrument applicable to every-day affairs for the betterment of mankind. Respected for his ability, beloved for his generous nature and keen sense of humor, he received numerous testimonials in the form of many gatherings in his honor and by the establishment of a scholarship in economic geology dedicated to the memory of his son John.

"To live in hearts we leave behind is not to die."

M. B. KILDALE.

SALT LAKE CITY, UTAH,
*July 10, 1943.*

# SCIENTIFIC NOTES AND NEWS

A. L. DU TOIT writes from Cape Town: the following items are for the Journal, although the news is belated because of my continued movements backwards and forwards in the interior in connection with the development of Blue Asbestos. W. P. DE KOCK is president of the Geological Society of South Africa and the Society has recently awarded the Draper Memorial Medal to L. T. NEL; H. J. R. WAY, formerly of the Geological Survey of Uganda has been appointed geologist of Swaziland for the British Government; PIERRE LEGOUX, chief of the Department of Mines, Brazzaville, has recently toured the Union and Rhodesia.

D. L. W. EVANS has resigned from the Board of Economic Warfare to return to the Climax Molybdenum Co.

D. H. MCLOUGHLIN, formerly dean of the College of Engineering of the University of California, is located in New York City as vice-president and director of Cerro de Pasco Copper Corp.

E. B. MATHEWS has retired as head of the Maryland Geological Survey and J. T. SINGEWALD, JR. has been appointed his successor as director of the Department of Geology, Mines and Water Resources.

R. A. RANTA, Lt. in the U. S. Army Air Forces and former graduate student in geology at Yale University, was killed in a plane crash in May.

T. A. LINK is chief geologist for Imperial Oil Ltd. "Canol Project," in the Mackenzie River Basin, Northwest Territories, Canada.

F. M. BULLARD, professor of geology and mineralogy at the University of Texas, taught courses in geology at the summer school of the National University of Mexico.

W. W. STALY, professor of mining at the University of Idaho, and ARTHUR ANDERSON, professor of geology at Cornell University, are studying the mineral possibilities of the mining districts in the east-central part of the state for the Idaho Bureau of Mines.

W. G. WOOLNOUGH has been appointed superintendent of the bibliographical and editorial section, Technical Practice Directorate, Ministry of Munitions in Melbourne, Australia.